

Temporal Masking Contributions of Inherent Envelope Fluctuations for Listeners with
Normal and Impaired Hearing

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Dedication

To my nephew, Harvey Svec, I can't wait to watch you grow up to be just as wonderful as your dad, Joe Svec.

Abstract

Gaussian noise (GN) simultaneous maskers yield higher masked thresholds for pure tones than low-fluctuation noise (LFN) simultaneous maskers for listeners with normal hearing. This increased residual masking is thought to be due to inherent fluctuations in the temporal envelope of Gaussian noise, but these masking effects using forward maskers have been previously unexamined. Because differences in forward masking due to age and hearing loss are known, the first study measured forward-masked detection thresholds for younger and older adults with normal hearing (NH) and older adults with hearing loss (HI) for a 4000 Hz pure-tone probe at a single masker-probe delay in narrowband noises with maximal (GN) or minimal (LFN) inherent envelope fluctuations. As predicted, results suggested that no effect of age was observed. Surprisingly, forward-masked threshold differences between GN and LFN, an estimate of the magnitude of the effect of inherent masker envelope fluctuations, were not significantly different for older HI listeners compared to younger or older NH listeners. Due to the surprising similarities between listeners with normal and impaired hearing, the second study was designed to assess effects of hearing loss on the slopes and magnitudes of recovery from forward maskers that varied in inherent envelope fluctuations for masker-probe delays of 25, 50, and 75 ms. In addition to measuring these effects centered at 4000 Hz, forward-masked thresholds were also measured at 2000 Hz, a region of better hearing for the HI listeners. As hypothesized, regardless of masker fluctuations, slopes of recovery from forward masking were shallower for HI than NH listeners in all conditions. At 4000 Hz, additional residual masking was greater in HI than NH listeners at the

longest masker-probe delays; whereas, no differences in additional residual masking between HI and NH listeners were observed for 2000 Hz. These results suggest that the masking effects from inherent envelope fluctuations persist to a greater degree and duration in regions of greater hearing loss. This persistence of the effects of inherent masker envelope fluctuations over time led to the consideration of measuring amplitude-modulated (AM) forward masking to estimate the contribution of modulation masking persistence. Studies measuring forward-masked modulation detection thresholds (MDTs), in which an AM masker preceded an AM signal, have recently revealed an effect termed “AM forward masking” (Wojtczak and Viemeister, 2005; Wojtczak *et al.*, 2011). The third study was designed to assess differences in AM forward masking at 1000 and 4000 Hz for NH and HI listeners. In line with predictions, an unmodulated GN masker yielded significantly more masking than an unmodulated LFN, suggesting that inherent masker envelope fluctuations contributed to the amount of AM forward masking across listener groups. Contrary to predictions, results suggested there were no differences in the amount of AM forward masking between NH and HI listeners, suggesting there is little effect of hearing loss on recovery from AM forward masking. Considering the combination of forward masking, AM forward masking, and listener uncertainty, the persistence of masker envelope fluctuation effects likely lead HI listeners to experience a shallower slope and longer time course of recovery than NH listeners. When attempting to recognize a speech segment after the offset of a masker when the signal-to-noise ratio is particularly unfavorable, the persistence of masking may play a role in the difficulty that HI listeners have relative to NH listeners for speech-in-modulated-noise recognition.

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CHAPTER ONE: INTRODUCTION

I. Background

For listeners with sensorineural hearing loss, reductions in frequency selectivity and cochlear nonlinearities lead to a number of auditory deficits (Moore, 1996), including reduced speech recognition in the presence of noise (Dubno and Schaefer, 1995).

Cochlear impairment has been shown to result in an increasingly linear response to signals in regions of hearing loss, relative to the compressive cochlear response of listeners with normal hearing (Ruggero *et al.*, 1997; Robles and Ruggero, 2001). While hearing aids increase the audibility of signals for many listeners with hearing loss, the benefits of amplification can be limited by physiological damage to the inner ear. Often the amplified sounds are distorted by the damaged ear, and any additional background noise impedes a listener's ability to understand speech. Differences in speech recognition performance between normal hearing (NH) and hearing-impaired (HI) listeners become more exaggerated when the noise is fluctuating in amplitude (e.g., Bacon *et al.*, 1998; Jin and Nelson, 2006). In amplitude-modulated (AM) noise, in which the level of the noise fluctuates over time, NH listeners can take advantage of brief reductions in amplitude between the temporal peaks of the noise; a phenomenon described as masking release. Even in cases of mild hearing loss, HI listeners experience less masking release than NH listeners (e.g., Dubno *et al.*, 2002).

For several years, investigators have been attempting to understand all of the contributing factors to this reduction in masking release that is observed for HI listeners.

French and Steinberg (1947) developed a method to estimate audibility, or the amount of the signal that is above hearing thresholds, across frequency regions important for understanding speech called the Articulation Index (AI). AI functions were initially developed by presenting a group of listeners with filtered speech to develop a series of perceptual weights thought to reflect the importance of speech in different frequency regions. In this way, estimates and predictions were derived for how much improvement a hearing aid should provide to a particular listener given a certain amount of hearing loss in a particular frequency region. It has been shown that, for listeners with mild-to-moderate hearing loss, AI predictions estimate performance fairly well in quiet settings and in the presence of steady-state noise when amplification is provided in regions of hearing loss (Dubno and Dirks, 1989). However, when the noise is fluctuating in level, predictions based on audibility have not entirely accounted for deficits in speech recognition performance for HI listeners (Jin and Nelson, 2006).

Investigators have been attempting to account for these apparent deficits for HI listeners by applying corrections for forward masking to AI (Rhebergen and Versfeld, 2005). Namely, it has been assumed that HI listeners don't recover in the "valleys" of the noise (e.g., forward masking) at the same rate as NH listeners (Ludvigsen, 1985). Rhebergen *et al.* (2006) asserted that a correction to the slope of recovery from forward masking may partially account for the poorer speech recognition scores for HI relative to NH listeners in AM noise. However, more recent results examining differences between sentence recognition in steady-state and modulated conditions have revealed that sentence recognition in modulated noise (Jin and Nelson, 2006) was highly correlated

with sentence recognition when speech was interrupted by silence (Jin and Nelson, 2009), suggesting that speech interrupted by either silence or noise may require similar perceptual integration of the signal. This relationship also suggests that a correction for traditional forward masking may not account for the entirety of the differences for speech-in-modulated-noise performance between NH and HI listeners.

Recently, Stone *et al.* (2012) have called into question the appropriateness of assuming that “steady-state” noise is not, in fact, modulated noise that significantly contributes to the amount of masking observed for speech-in-noise recognition. The authors attempted to examine whether or not inherent envelope fluctuations within noise affected the amount of masking release observed when NH listeners were presented with speech in “steady-state” or AM maskers. Listeners were asked to repeat sentences when presented with speech in either Gaussian noise (GN), with intact inherent fluctuations, or “low-noise noise”, referred to here as “low-fluctuation noise” (LFN), with these inherent fluctuations minimized. Each masker was presented in either a steady-state condition or an AM condition. Because results suggested that masking release was maximally reduced when comparing performance in the steady-state LFN and AM LFN conditions, the authors asserted that the inherent fluctuations in what we consider to be “steady-state” noise may actually play a larger role in what we have been calling “masking release” than previously demonstrated.

Not only have inherent fluctuations of a masker been shown to affect the amount of masking in a speech recognition task, this phenomenon has been observed in simple tone detection tasks (e.g., Savel and Bacon, 2003). Savel and Bacon (2003) measured

masked thresholds for a 4000 Hz pure-tone signal in the presence of either a narrowband GN or LFN simultaneous masker in NH listeners. The authors asserted that fluctuations in the envelope of the GN were likely responsible for its increased masking effectiveness.

Because there continued to be some ambiguity about the effects of inherent masker envelope fluctuations after the offset of a masker (forward masking), the initial motivation for the three studies discussed here was to compare forward-masked thresholds between NH and HI listeners for maskers that varied in their inherent envelope fluctuations. We hypothesized that any differences in the effects of masker envelope fluctuations observed between NH and HI listeners may partially explain why HI listeners do not appear to “recover” after the offset of a masker, or during the valley of a AM masker, to the same magnitude as NH listeners when attempting to access a signal.

II. Experiment One

To initially examine the effects of inherent masker envelope fluctuations as a function of age and hearing loss, the first study, described in Chapter Two, measured forward-masked detection thresholds for younger and older adults with normal hearing and older adults with hearing loss for a 4000 Hz pure-tone probe in narrowband noises with maximal (GN) or minimal (LFN) inherent envelope fluctuations.

The two primary research questions of this initial study were as follows: 1) Do inherent masker envelope fluctuations result in higher forward-masked thresholds for GN than LFN maskers for younger normal hearing listeners?; and 2) If so, does this increased masking change as a function of age or hearing loss? We predicted that forward-masked

thresholds would be highest for maskers with maximal inherent envelope fluctuations (GN) and lowest for maskers with minimal inherent envelope fluctuations (LFN). Based on previous findings (Koopman *et al.*, 2008), we predicted that threshold differences (GN vs. LFN) would be larger for HI than for NH listeners. Because age-related differences in forward masking have been shown to be minimal (e.g., Dubno *et al.*, 2003), we predicted no age-related differences for forward-masked thresholds between maskers with maximal or minimal inherent masker envelope fluctuations, relative to younger normal hearing listeners.

Due to unexpected similarities in the results between younger normal hearing and older hearing-impaired listeners, questions remained regarding the effects of inherent envelope fluctuations at longer masker-probe delays. The slope of recovery from forward masking is shallower in HI than in NH listeners due to reduced cochlear nonlinearities (e.g., Ludvigsen, 1985; Oxenham and Moore, 1997), but the time constant of recovery from forward masking is expected to be relatively similar for NH and HI listeners (e.g., Oxenham and Bacon, 2003). However, recovery from inherent envelope fluctuations (GN vs. LFN) at multiple masker-probe delays remained unknown for both NH and HI.

III. Experiment Two

Consequently, the second study, described in Chapter Three, was designed to assess effects of hearing loss on the slopes and magnitudes of recovery from forward maskers that varied in inherent envelope fluctuations for masker-probe delays of 25, 50, and 75 ms. In addition to measuring these effects centered at 4000 Hz (e.g., first study,

Chapter Two), forward-masked thresholds were also measured at 2000 Hz, a region of better hearing for the HI listeners. Functions relating forward-masked thresholds to masker-probe delay were used to estimate slopes of recovery from forward masking. Additional masking attributed to inherent envelope fluctuations (GN-LFN) was used to determine the magnitude of recovery from inherent envelope fluctuations across masker-probe delays.

As predicted, slopes of recovery from forward masking were shallower for HI than NH listeners. At 4000 Hz, additional masking was greater in HI than NH listeners at the longest masker-probe delays. These results suggest that the masking effects from inherent envelope fluctuations persist to a greater degree and duration in regions of greater hearing loss.

This persistence of the effects of inherent masker envelope fluctuations over time led to the consideration of measuring amplitude-modulated (AM) forward masking to estimate the contribution of sequential modulation masking persistence.

IV. Experiment Three

Studies measuring forward-masked modulation detection thresholds (MDTs), in which an amplitude-modulated masker preceded an amplitude-modulated signal, have recently revealed an effect described as amplitude-modulated (AM) forward masking (Wojtczak and Viemeister, 2005; Wojtczak *et al.*, 2011). Using a similar strategy to Wojtczak and Viemeister (2005), the third study measured differences in AM forward

masking at 1000 and 4000 Hz for NH and HI listeners using continuous and non-continuous masker and signal carriers.

Results suggested that, as predicted, masked modulation detection thresholds (MDTs) improved as masker-probe delay increased for both NH and HI listeners. For the non-continuous carrier, the GN yielded more masking than the LFN, as predicted. Contrary to predictions, HI listeners performed very similarly to NH listeners for all masked conditions.

Summaries of all three experiments, as well as future implications, are discussed in Chapter Five.

CHAPTER TWO: EFFECTS OF INHERENT ENVELOPE FLUCTUATIONS IN FORWARD MASKERS FOR LISTENERS WITH NORMAL AND IMPAIRED HEARING

I. INTRODUCTION

A. Effects of Masker Fluctuations on Recognition and Detection

The most commonly reported complaint of listeners with hearing loss is difficulty understanding speech in the presence of background noise. Differences in masked speech recognition in noise between listeners with normal hearing (NH) and listeners with sensorineural hearing loss (HI) are larger when the noise is fluctuating in amplitude (e.g., Bacon *et al.*, 1998; Jin and Nelson, 2006). In amplitude-modulated noise, NH listeners can take advantage of the better signal-to-noise ratio provided by brief reductions in the

level of the noise to improve speech understanding compared to that in steady-state Gaussian noise (GN) (Bacon *et al.*, 1998; Dubno *et al.*, 2003; Jin and Nelson, 2006). This improvement, or masking release, is smaller for HI than for NH listeners, even those with mild hearing loss (e.g., Dubno *et al.*, 2002), but the factors that contribute to the reduction in masking release for HI listeners remain unclear.

While amplitude-modulated maskers with relatively low modulation frequencies generally result in improvements in speech recognition relative to that in steady-state maskers, maskers with rapid temporal envelope modulations, or fluctuations, may not improve performance. For example, Stone *et al.* (2012) showed that inherent rapid envelope fluctuations within Gaussian noise can decrease speech recognition for NH listeners as compared to performance in a noise with minimal envelope fluctuations, such as a “low-noise noise” (Pumplin, 1985), referred to here as “low-fluctuation noise” (LFN). The authors concluded that masking release defined in the traditional way is primarily related to a brief cessation of “modulation masking” and less related to reductions in “energetic masking.”

Energetic masking refers primarily to an increase in the energy of an unmodulated masker that falls within the passband of the auditory filter(s) that is processing the signal, which yields an increase in masked threshold (e.g., Green and Swets, 1966). In contrast, modulation masking refers to the effect of a masker’s amplitude modulations on detection of an amplitude-modulated signal when the masker and signal are in close spectral proximity, or are applied to the same carrier frequency (e.g., Bacon and Grantham, 1989).

Modulation masking describes any increase in masked threshold observed for modulated masker conditions relative to unmodulated masker conditions.

Although the term modulation masking is typically reserved for situations in which both the signal and the masker are amplitude modulated, rapid masker envelope fluctuations have also been shown to affect detection of unmodulated pure-tone signals. Savel and Bacon (2003) measured masked detection thresholds for a 4000-Hz pure tone (10 or 200 ms) in the presence of three simultaneous maskers: Gaussian noise, low-fluctuation noise (Kohlrausch *et al.*, 1997), or a pure tone. The bandwidth of each noise masker was 500 Hz, and each masker was placed either lower or higher in frequency than the signal (e.g., 3053-3553 Hz or 4500-5000 Hz); the pure-tone masker was either 3553 or 4500 Hz. Gaussian noise produced substantially more masking than low-fluctuation noise or pure-tone maskers, and low-fluctuation noise and pure tones produced comparable amounts of masking. Similar to the conclusions of Stone *et al.* (2012) related to modulation masking, Savel and Bacon (2003) proposed that the rapid fluctuations in the temporal envelope within the Gaussian noise were responsible for its increased masking effectiveness. For fluctuating maskers, the amount of fluctuation can be quantified by the crest factor, or the ratio between peak amplitude and the root-mean-square (rms) amplitude within the temporal envelope of the waveform (e.g., Hartmann and Pumplin, 1988). Crest factors provide an estimate of the relationship between the power in the peaks of the amplitude fluctuations compared to the overall energy of the noise. In the current study, noises described as having “maximal” fluctuations have relatively high crest factors whereas noises described as having “minimal” fluctuations

have relatively low crest factors.

Hartmann and Pumplin (1988) suggested that, for masker bandwidths exceeding a critical band, the envelope of a low-fluctuation noise masker will no longer be flat and its masking properties will mirror those of Gaussian noise. To test this notion, Kohlrausch *et al.* (1997) measured masked detection thresholds for pure-tone probes centered at 1000 and 10,000 Hz in the presence of either Gaussian noise or low-fluctuation noise simultaneous maskers with a range of bandwidths. The results were consistent with the views of Hartmann and Pumplin (1988) in that differences in masked thresholds between Gaussian noise and low-fluctuation noise were maximal (GN>LFN) when the bandwidth of the two maskers was 25-50 Hz, which is approximately one-third of an equivalent rectangular bandwidth (ERB, Glasberg and Moore, 1990), an estimate of auditory filter width that is comparable to the notion of a critical band. Wider and narrower masker bandwidths yielded smaller masked threshold differences between Gaussian noise and low-fluctuation noise. As such, differences between rapid masker envelope fluctuations are expected to be maximal (GN>LFN) when the bandwidth of the two maskers is $\sim 1/3$ ERB, or sufficiently within the bandpass of an auditory filter.

B. Effects of Fluctuations in Forward Maskers

Recovery from forward masking refers to the ability to detect a signal at some time point after the offset of a steady-state masker or the offset of an amplitude peak within a modulated masker. In the current study, a “recovery function” refers to the decrease in masked threshold as a function of the increase in duration between the offset of the masker and the onset of the signal (or masker-signal delay); the rate of change in

masked threshold is determined by the slope of the function and the function's time constant refers to the briefest masker-signal delay that results in a return to the signal's quiet threshold. The time constant for the recovery function is assumed to depend on neural mechanisms, such as integration and/or adaptation (Oxenham, 2001), whereas the slope of the function is largely driven by intact (NH) or reduced (HI) cochlear nonlinearities (Oxenham and Moore, 1997; Oxenham and Bacon, 2003). In NH listeners, the time constant using a relatively short-duration signal is ~200 ms (e.g., Jesteadt *et al.*, 1982; Ludvigsen, 1985). Following the offset of a high-level masker, the slope of the recovery function is relatively steep in NH listeners, but shallower in HI listeners (e.g., Oxenham and Moore, 1997). This decrease in slope with hearing loss is assumed to be due to the reduced dynamic range in HI listeners, which is a consequence of reduced cochlear nonlinearities (Oxenham and Bacon, 2003).

C. Effects of Fluctuations in Modulated Forward Maskers

An effect described as analogous to forward masking of audio frequencies has been observed in the modulation masking domain when an amplitude-modulated masker preceded an amplitude-modulated signal applied to the same broadband carrier (Wojtczak and Viemeister, 2005). Extending the findings of Wojtczak and Viemeister (2005) to HI listeners, Koopman *et al.* (2008) presented NH and HI listeners with a 1000-Hz signal carrier and a 2000-Hz masker carrier, both sinusoidally amplitude modulated (SAM) at 8 Hz, including variable masker-signal delays. Results revealed more modulation detection interference for HI than NH listeners when measured at comparable sound pressure levels (dB SPL), even when the masker preceded the signal in time (e.g., forward masking).

Similar to modulation masking, modulation detection interference describes the disruption of a listener's ability to detect amplitude modulation of a signal in the presence of an amplitude-modulated masker. In contrast to modulation masking, the term modulation detection interference is used when the maskers and signals are imposed upon separate carriers and are spectrally distant from each other (e.g., Yost and Sheft, 1989).

Taken together, these results suggest that inherent rapid envelope fluctuations within otherwise “steady-state” maskers yield more masking than noises with flatter envelopes, at least in NH listeners, especially when masker bandwidths are less than a critical band (Hartmann and Pumplin, 1988) or an ERB (Kohlrausch *et al.*, 1997). Moreover, if the increased effect of modulated forward maskers observed in HI listeners (Koopman *et al.*, 2008) is relevant for detecting pure-tone signals, HI listeners may be more susceptible to the effects of rapid envelope fluctuations in forward maskers than NH listeners. If forward maskers with minimal inherent envelope fluctuations result in elevated masked thresholds for HI listeners, relative to NH listeners, then differences in masked thresholds between NH and HI listeners for forward maskers with maximal inherent envelope fluctuations may define recovery from inherent envelope fluctuations that exceed recovery from forward masking.

D. Research Questions

To assess sensitivity to inherent masker envelope fluctuations, the current study measured forward-masked detection thresholds for a 4000 Hz pure-tone signal (probe) in narrower and wider bandwidth noises with maximal or minimal inherent envelope fluctuations. To assess effects of age and hearing loss, participants were younger and

older adults with normal hearing and older adults with hearing loss. Forward-masked thresholds were measured for four maskers: 1) 1/3 ERB LFN - Inherent masker fluctuations are reduced, flattest temporal envelope; 2) 1 ERB LFN - Inherent masker fluctuations are reduced, but minor temporal envelope fluctuations are likely created as signals are processed through multiple auditory filters; 3) 1 ERB GN – Inherent masker fluctuations are intact, but flatter temporal envelope due to wider masker bandwidth; and 4) 1/3 ERB GN - Inherent masker envelope fluctuations are intact, and greater due to narrower masker bandwidth.

The experiment was designed to answer two primary research questions. The first question focused on the relationship between inherent masker envelope fluctuations and forward-masked thresholds for younger NH adults. Based on results with simultaneous maskers (Savel and Bacon, 2003; Kohlrausch *et al.*, 1997), we predicted that forward-masked thresholds would be highest in 1/3 ERB GN with maximal inherent masker envelope fluctuations and lowest in 1/3 ERB LFN with minimal inherent masker envelope fluctuations. We further predicted that forward-masked thresholds for the wider bandwidth maskers (1 ERB GN vs. LFN) would differ less due to their more similar temporal envelopes.

The second research question focused on the contribution of hearing loss and age on the effectiveness of forward maskers with inherent envelope fluctuations. Based on previous findings related to modulation detection interference with hearing impairment (Koopman *et al.*, 2008), we predicted that threshold differences for the narrower bandwidth maskers (1/3 ERB GN vs. LFN) would be larger for HI than for NH listeners.

In contrast, based on the absence of age-related differences in forward masking (e.g., Dubno *et al.*, 2003), we predicted no age-related differences in effectiveness of inherent masker envelope fluctuations.

II. METHODS

A. Participants

Twenty five adult listeners (7 males, 18 females) participated in this experiment. For the younger adults with NH (YNH, $n=8$, age 22-30 years), pure-tone thresholds in the test ear were ≤ 20 dB HL at audiometric frequencies from 250 to 8000 Hz (ANSI, 2004). For the older adults with NH (ONH, $n=8$, age 62-66 years), pure-tone thresholds in the test ear were ≤ 20 dB HL at audiometric frequencies from 250 to 4000 Hz and ≤ 25 dB HL at audiometric frequencies from 6000 to 8000 Hz. For older adults with HI (OHI, $n=9$, age 60-89 years), pure-tone thresholds were < 50 dB HL at 250, 500, and 1000 Hz, between 25 and 55 dB HL at 2000 and 4000 Hz, and between 25 and 70 dB HL at 8000 Hz. HI listeners with conductive or mixed hearing losses were not eligible for participation. Listeners were compensated for their participation.

The left panel of *Fig. 2.1* contains mean (filled symbols) and individual (dashed lines) pure-tone thresholds in the test ear measured in dB HL (ANSI, 2004) and converted to dB SPL for the three groups of listeners. The test ear was the better ear for all listeners in the YNH and ONH groups. For the OHI listeners, if both ears met the inclusion criteria, the ear with a better threshold at 4000 Hz was chosen for testing. If thresholds were identical at 4000 Hz, the right ear was chosen for testing. The right panel

of *Fig. 2.1* contains mean (filled symbols) and individual (open symbols) pure-tone thresholds (in dB SPL) in the test ear for the 10-ms, 4000-Hz probe. Mean thresholds were 19.7, 25.6, and 59.2 dB SPL for the YNH, ONH, and OHI groups, respectively.

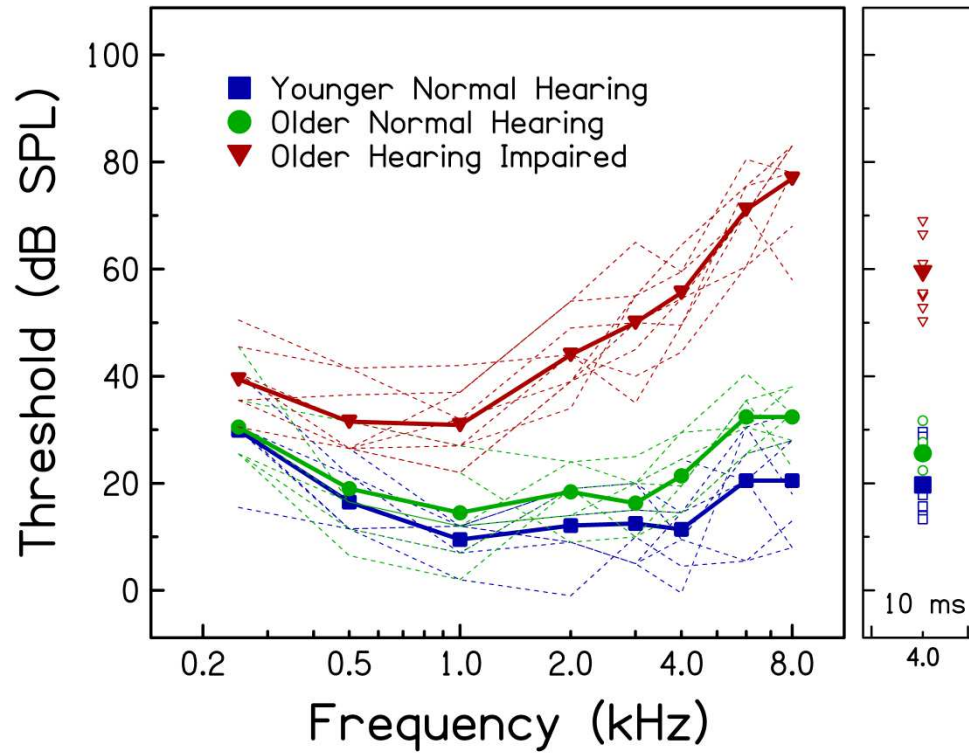


FIG. 2.1. Mean (filled symbols) and individual (dashed lines) pure-tone thresholds measured (in dB HL and converted to dB SPL) in the test ear for 250-ms signals for three groups (left panel). Mean (filled) and individual (open) pure-tone thresholds (in dB SPL) in the test ear for the 10-ms, 4000-Hz probe for three groups (right panel).

B. Apparatus and Stimuli

Each signal was generated at a sampling rate of 44,100 Hz and produced via a Matlab script file matched with a Lynx TWO-B soundcard, including an A/D and D/A Type 24-bit, multi-level delta-sigma converter, and a built-in antialiasing filter with a cutoff frequency of 21,300 Hz. Signals were presented through a Tucker-Davis Technologies (TDT) HB5 headphone buffer driving an ER-5A Etymotic insert earphone.

No earphone was placed in the non-test ear. The duration of the 4000-Hz pure-tone probe was 10 ms, including 5-ms raised cosine onset and offset ramps. Each of four 400-ms maskers, including 5-ms raised cosine onset and offset ramps, was centered at 4000 Hz: (a) GN with a bandwidth of 463 Hz (1 ERB) and cutoff frequencies of 3775 and 4238 Hz; (b) GN with a bandwidth of 154 Hz (1/3 ERB) and cutoff frequencies of 3924 and 4078 Hz, and (c) two LFNs with bandwidths and cutoff frequencies identical to those of the GNs. Both the GNs and LFNs were generated following a procedure described by Buss *et al.* (2006), which had been adapted from the method for generating LFN developed by Kohlrausch *et al.* (1997). A band of GN centered at 4000 Hz for each bandwidth (463 Hz and 154 Hz) was divided in the time domain by the Hilbert envelope and then multiplied by the original spectral region (463 Hz and 154 Hz wide bands) in the frequency domain. For the LFN, the multiplication was repeated 10 times, resulting in a temporal envelope with minimal inherent fluctuations. To quantify masker fluctuation, peak-to-rms ratios (crest factors, in dB) were calculated for 100 noise samples generated for each of the four maskers; mean crest factors and standard deviations were computed. As expected, mean crest factors were higher for GN than LFN. In addition, standard deviations were much higher for GN than LFN.

Initiation of the masker occurred 50 ms after the beginning of the interval. The probe was presented 25 ms after the offset of the masker. The overall level of the masker was fixed at 80 dB SPL. See *Fig. 2.2* for a schematic of the waveforms for the probe, 1 ERB GN (top) and 1 ERB LFN (bottom). Inside the double-walled, sound-treated booth,

a computer monitor displayed the timing of signal presentations; a touchscreen interface was used to record participant responses.

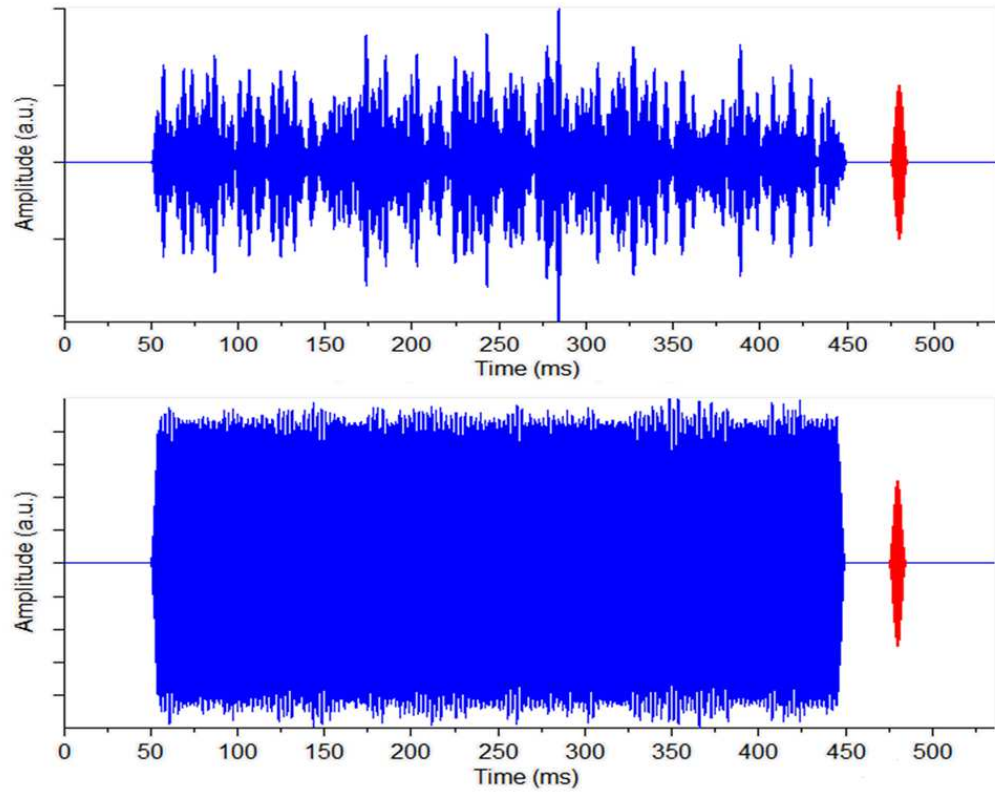


FIG. 2.2. Waveforms showing 400-ms maskers (left) and 10-ms probe (right), for Gaussian noise (GN) (top) and low-fluctuation noise (LFN) (bottom).

C. Procedures

Detection thresholds for the 10-ms probe at 4000 Hz were measured in quiet using a three-interval forced choice (3IFC) two-up, one-down adaptive psychophysical procedure tracking 70.7% correct on the psychometric function (Levitt, 1971). Each block ceased after 12 reversals. Each trial contained three 600-ms observation intervals, one of which contained the probe, separated by a 500-ms inter-stimulus interval.

Participants received feedback for correct and incorrect responses. The starting level for the probe was 50 dB SPL for NH listeners and 80 dB SPL for HI listeners. Initial step size was 5 dB, changing to 2 dB after the first two reversals. Thresholds were calculated as the mean probe level in dB SPL for the final 8 reversals. Mean thresholds for each condition were based on at least three blocks. If the standard deviation of a block exceeded 5 dB, a fourth block was obtained. In these cases, the mean of all four threshold estimates was the final probe threshold. The right panel of *Fig. 2.1* displays probe thresholds measured in quiet. A very similar procedure, with the exception of probe starting levels, was used to determine masked thresholds by keeping the masker level constant at 80 dB SPL and adaptively varying the probe level.

For measuring forward-masked thresholds, a training session was completed before data collection to familiarize listeners with various maskers, using the 1 ERB GN and LFN maskers. During training, the starting level for the probe was 80 dB SPL for the NH listeners and 95 dB SPL for the HI listeners. Once the participant's performance reached a standard deviation of <5 dB within a block, training for that condition ceased. Once data collection for measuring masked thresholds commenced, starting levels for the probe were 20 dB SL re: masked threshold determined during training.

The testing conditions were blocked by masker bandwidth (1 ERB or 1/3 ERB) and masker type (GN or LFN) and randomized by a number assigned to each of the four maskers. Testing did not exceed four hours over multiple visits, including informed consent, measurement of audiometric thresholds, training, and data collection. Frequent breaks were offered to participants, as needed.

Effects of masker type (LFN, GN) and bandwidth (1/3 ERB, 1 ERB) on forward-masked thresholds were assessed with a repeated-measures analysis of variance (ANOVA) with one grouping variable (YNH, ONH, OHI). Relationships between masked and quiet probe thresholds were evaluated using correlational analyses. Effects were considered significant with $p < 0.05$. The hypotheses predicted main effects for all three factors, and an interaction between masker type, masker bandwidth, and participant group. The hypotheses also predicted significant correlations between masked and quiet probe thresholds for all listener groups. However, weaker associations were predicted for maskers with maximal inherent envelope fluctuations than for maskers with minimal inherent envelope fluctuations and for HI listeners, due to larger individual differences in masked thresholds using stimuli with fluctuating temporal envelopes (e.g., Eddins, 2001) and among HI listeners (e.g., Jin and Nelson, 2006).

III. RESULTS

As hypothesized, rapid inherent masker envelope fluctuations had a significant effect on forward-masked pure-tone detection. GN yielded significantly higher masked thresholds than LFN for all participant groups [$F(1, 22) = 48.04$, $p < 0.001$] (*Fig. 2.3*). Masker bandwidth had a significant effect as well. Masked threshold differences between GN and LFN were significantly larger for narrower bandwidth maskers (1/3 ERB GN \gg 1/3 ERB LFN) than for wider bandwidth maskers (1 ERB GN $>$ 1 ERB LFN) [$F(1, 22) = 15.97$, $p < 0.05$], and the effect of bandwidth was greater for LFN than GN across listener groups [$F(1, 22) = 146.06$, $p < 0.05$]. For the 1 ERB bandwidth, mean

masked thresholds were 59.5 (YNH), 66.2 (ONH), and 81.5 (OHI) dB SPL for the GN masker and 53.5 (YNH), 59.3 (ONH), and 74.8 (OHI) dB SPL for the LFN masker. Similarly, for the 1/3 ERB bandwidth, mean masked thresholds were 57.6 (YNH), 65.8 (ONH), and 81.9 (OHI) dB SPL for the GN masker and 47.3 (YNH), 51.9 (ONH), and 72.3 (OHI) dB SPL for the LFN masker.

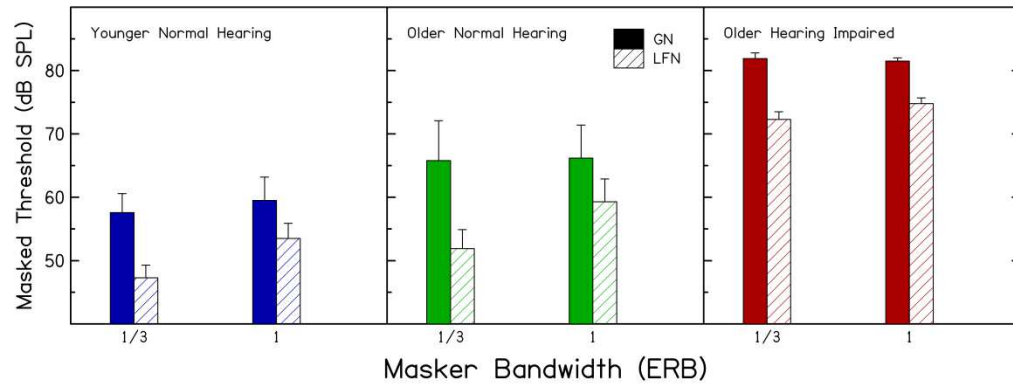


FIG. 2.3. Mean (± 1 SE) forward-masked thresholds (in dB SPL) for two forward maskers (GN, filled; LFN, striped) and two masker bandwidths (1/3 ERB, 1 ERB) for three groups.

There was no significant effect of listener age. As predicted for the ONH group, pairwise comparisons of the between subjects factor showed that masked thresholds (*Fig. 2.3*) and mean differences in masked thresholds (*Fig. 2.4*) were not significantly different from those for the YNH group ($p > 0.05$). In contrast, there was a significant effect of hearing loss. Masked thresholds for the OHI group were significantly higher than for the other two groups ($p < 0.001$), which is at least partially due to their elevated probe thresholds. However, contrary to predictions, mean differences in masked thresholds between GN and LFN maskers for OHI listeners (1 ERB = 6 dB, 1/3 ERB = 10.4 dB) were not significantly different from those for the YNH (1 ERB = 6.6 dB, 1/3 ERB = 9.7 dB) or the ONH (1 ERB = 6.9 dB, 1/3 ERB = 13.9 dB) listeners ($p > 0.05$).

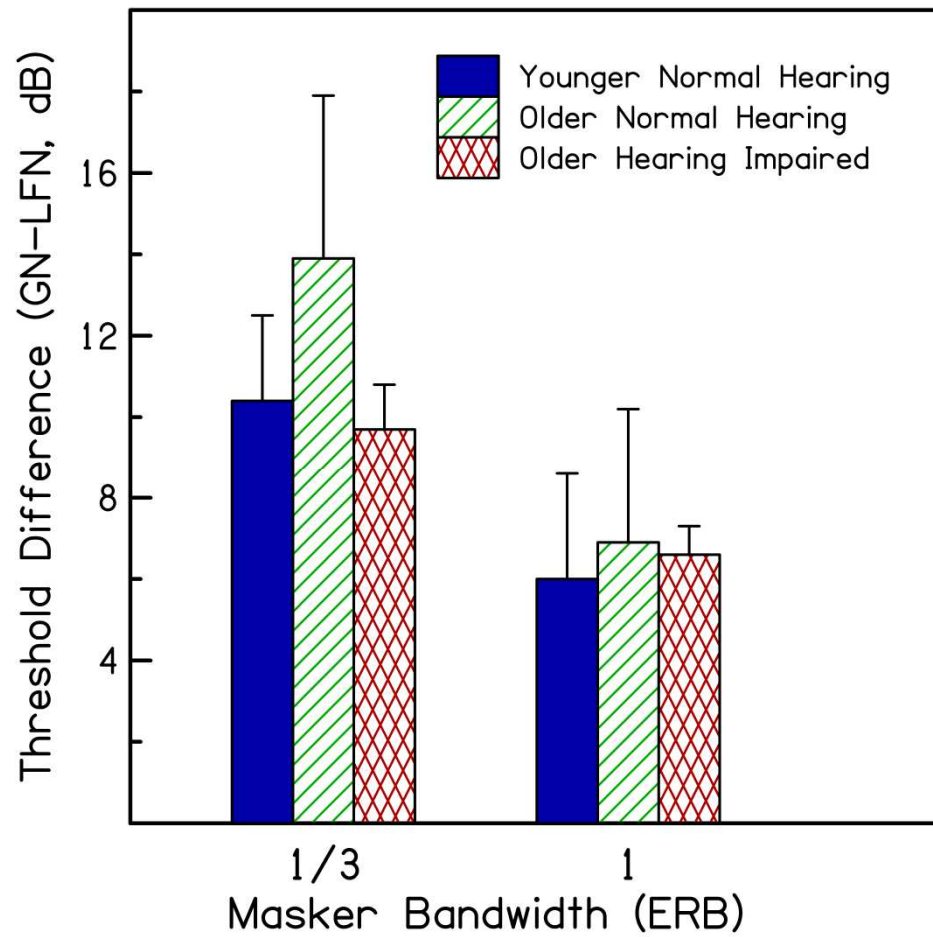


FIG. 2.4. Mean (61 SE) differences in masked thresholds (in dB) between GN and LFN for each masker bandwidth (1/3 ERB and 1 ERB) for three groups.

Across all listeners, masked thresholds were highly correlated with quiet probe thresholds (see *Fig. 2.5*) ($r = 0.76-0.93$, $p < 0.05$); however, when evaluated within listener groups, these relationships for each masker condition were no longer significant in the OHI group ($p > 0.05$). For both the YNH and ONH groups, small increases in quiet probe thresholds resulted in large increases in masked thresholds, especially for the GN maskers. In contrast, masked thresholds remained relatively constant with increases in quiet probe thresholds for listeners with hearing loss, suggesting that the dependence on

quiet probe thresholds may be limited for listeners with reduced dynamic ranges at the probe frequency.

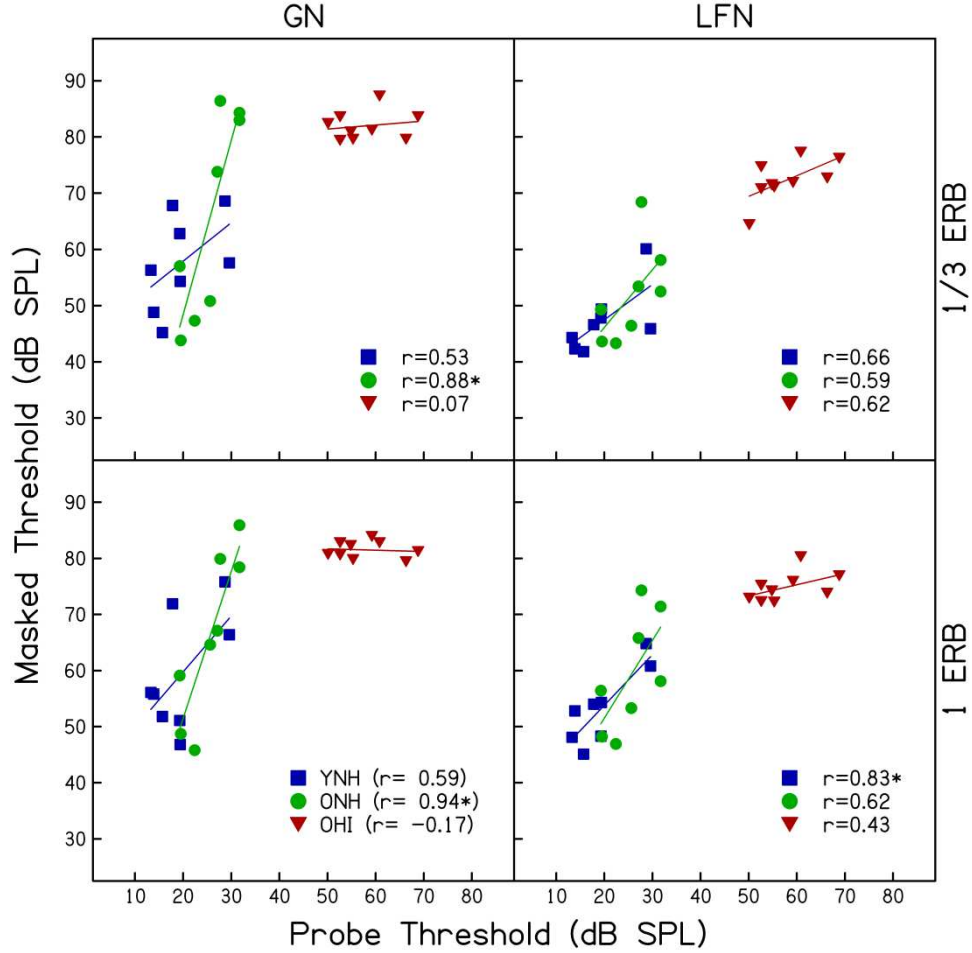


FIG. 2.5. Forward-masked thresholds (in dB SPL) for each masker (GN and LFN) and masker bandwidth (1/3 ERB and 1 ERB) plotted against probe thresholds for YNH (squares), ONH (circles), and OHI (triangles) listeners. The lines represent the linear relationship between forward-masked threshold and probe threshold for the corresponding color (online) and listener group (YNH, ONH, OHI, respectively). Within group correlations are shown next to the corresponding symbols in each panel.

IV. DISCUSSION

Results of the current study demonstrate that forward maskers with greater inherent envelope fluctuations (Gaussian noise) yielded higher thresholds than those with

reduced inherent envelope fluctuations (low-fluctuation noise) for younger and older normal hearing listeners and older hearing-impaired listeners. These results suggest that the effects of inherent masker envelope fluctuations previously observed in simultaneous masking for pure tones (Kohlrausch *et al.*, 1997; Savel and Bacon, 2003) and speech recognition (Stone *et al.*, 2012) also occur in forward masking. The precise mechanisms responsible for this increased masking are not clear, but they may be explained, in part, by differences in detection cues and modulation masking attributes of Gaussian noise and low-fluctuation noise. Because differences between masked thresholds with maximal and minimal inherent envelope fluctuations obtained from listeners with normal and impaired hearing were similar, cochlear impairment may not affect recovery from masker envelope fluctuations after controlling for recovery from forward masking.

A. Detection Cues

To detect a short-duration pure-tone probe in the presence of a simultaneous noise masker, a listener relies on different cues depending on the bandwidth and temporal properties of the masker. In a narrowband noise masker, a listener may be attending to the onset and offset of the probe, or a change in the temporal envelope to detect the signal (Oxenham, 1998). Variability of inherent fluctuations in the temporal envelope of the stimuli disrupt these envelope-based cues and increase listener uncertainty more for a Gaussian noise than for a low-fluctuation noise masker (Buss *et al.*, 2006; Eddins, 2001).

In forward masking, the reduction in temporal envelope fluctuations associated with a low-fluctuation noise masker may increase the change in the overall temporal envelope that is time-locked to the onset of the probe, providing more robust envelope-

based cues for detecting the probe and resulting in lower masked thresholds. In the current study, for the condition with the narrowest bandwidth noise with minimal inherent envelope fluctuations (1/3 ERB LFN), listeners may have perceived a clear change in the temporal envelope that occurred between the offset of the masker and the onset of the probe, a robust envelope-based detection cue. Whereas, in the two masker conditions with maximum masker envelope fluctuations (1 ERB GN and 1/3 ERB GN), the temporal envelope-based detection cue was maximally disrupted, resulting in higher masked thresholds. In the wider bandwidth noise with reduced inherent envelope fluctuations (1 ERB LFN), exceeding a critical band likely introduced minor fluctuations in the masker envelope, which may have somewhat disrupted the temporal envelope-based cue, resulting in slightly elevated masked thresholds relative to the masker envelope with the least amount of inherent fluctuations (1/3 ERB LFN). In this way, rapid inherent envelope fluctuations in a forward masker can result in higher masked thresholds for a short-duration probe by varying the amount of disruption to the envelope-based cue used for detecting the probe.

B. Effects of Hearing Loss and Forward Masking

Contrary to predictions, the relative masking effectiveness of noises that vary in their inherent envelope fluctuations did not change with hearing loss, at least for the 25-ms masker-probe delay included in the current study. If recovery from forward masking is dependent on neural mechanisms that determine the time constant (e.g., Oxenham, 2001), in combination with peripheral mechanisms (cochlear compression) that contribute to the slope of recovery (e.g., Oxenham and Moore, 1997), sensorineural

hearing loss of cochlear origin should affect the slope of recovery due to changes in cochlear nonlinearities, but should leave the time constant relatively intact (e.g., Oxenham and Bacon, 2003). Because the results of the current study suggest that “recovery” from the inherent envelope fluctuations of Gaussian noise relative to low-fluctuation noise is similar for NH and HI listeners at this masker-probe delay (see *Fig. 2.4*), recovery from rapid envelope fluctuations may be unaffected by differences in cochlear nonlinearities between NH and HI listeners and a portion of this recovery may occur beyond the cochlea. Thus, our unexpected finding of similar recovery from rapid envelope fluctuations for NH and HI listeners suggests that this recovery and recovery from forward masking may arise from somewhat distinct mechanisms.

C. Effects of Hearing Loss and Modulation Masking

As discussed, listeners may have perceived a change in the temporal envelope that occurred between the offset of the masker and the onset of the probe and used this cue to detect the probe. When this temporal envelope-based cue was disrupted due to inherent fluctuations in the masker envelope, a less robust cue for probe detection resulted in higher masked thresholds. If changes in the temporal envelope of the masker affect a listener’s ability to take advantage of envelope-based detection cues related to the onset of the probe, these effects may be comparable to the effects of modulation masking. For example, forward masking in conjunction with modulation masking may partially explain increased modulation detection interference in HI, relative to NH listeners (Koopman *et al.*, 2008).

Although the use of an unmodulated pure-tone probe calls into question the role of modulation masking in the current experiment, our results nevertheless suggest that maskers with rapid inherent envelope fluctuations result in more masking than maskers with reduced inherent fluctuations. The effectiveness of maskers that vary in their inherent envelope fluctuations did not differ between NH and HI listeners at a relatively short (25-ms) masker-probe delay. However, effects of hearing loss on masker effectiveness for various fluctuating forward maskers for longer masker-probe delays remains unknown.

D. Future Directions

Measuring masked thresholds under conditions in which maskers and probes are separated in time and frequency may reveal differences in slopes and time constants of recovery from these masking mechanisms. Using longer masker-probe delays will provide a better test of the hypothesis that energetic and modulation masking interact differently for NH and HI listeners across time due to differences in slopes of recovery from forward masking. In addition, measuring analogous conditions at lower frequencies (such as 2000 Hz) will allow masked thresholds to be measured in HI listeners in regions with wider dynamic ranges.

Similarly, changes in masker effectiveness as the masker and probe are separated in frequency may isolate the effects of hearing loss related to the upward spread of forward masking and minimize confusion effects (Neff, 1986), which may contribute to elevated on-frequency forward-masked thresholds in narrowband maskers.

V. CONCLUSIONS

1. As predicted, forward-masked thresholds were higher for maskers with greater inherent envelope fluctuations than for less fluctuating maskers for younger adults with normal hearing. Increases in inherent masker fluctuations may have disrupted detection of the temporal envelope-based cue between the masker offset and probe onset, resulting in elevated masked thresholds.
2. As predicted, no significant effect of listener age on forward-masked thresholds was observed. However, contrary to predictions, mean differences in forward-masked thresholds between Gaussian and low-fluctuation maskers for older adults with hearing loss were similar to those for younger and older adults with normal hearing. Results suggest that recovery from inherent masker envelope fluctuations and recovery from forward masking may arise from different mechanisms. Given the similarities in the recovery from inherent masker envelope fluctuations for listeners with normal and impaired hearing, a portion of this recovery may occur beyond the cochlea.

CHAPTER THREE: INHERENT ENVELOPE FLUCTUATIONS IN FORWARD MASKERS: EFFECTS OF MASKER-PROBE DELAY FOR LISTENERS WITH NORMAL AND IMPAIRED HEARING

I. INTRODUCTION

A. Effects of Forward Masker Envelope Fluctuations

In a previous study (Svec *et al.*, 2015^a), forward-masked thresholds were higher for maskers with maximal (Gaussian noise, GN) than minimal (Low-fluctuation noise, LFN) inherent envelope fluctuations, and masked threshold differences (GN-LFN) were similar for normal-hearing (NH) and hearing-impaired (HI) adults when measured at 4000 Hz for a single masker-probe delay of 25 ms. The similar pattern observed for NH and HI listeners gave rise to additional questions regarding additional masking due to inherent envelope fluctuations and the mechanisms that may contribute to differences in forward masking for maskers that differ in their inherent envelope fluctuations.

In regards to differences in detection cues for a forward-masked probe, listeners may use a perceived change in the temporal envelope between the offset of the masker and the onset of the probe as a cue to detect the probe. Variability of inherent envelope fluctuations contributes to listener uncertainty by disrupting these envelope-based cues. This uncertainty is increased more for narrowband GN than for LFN maskers (Buss *et al.*, 2006; Eddins, 2001). A change in the temporal envelope that is time-locked to the onset or offset of the probe likely leads to robust envelope-based cues for LFN maskers, resulting in lower masked thresholds than for GN maskers.

Presumably, these envelope detection cues were similarly robust for both NH and HI listeners at a relatively short masker-probe delay (25 ms), given that the masking effectiveness of noises that varied in their inherent envelope fluctuations did not change

with hearing loss. The slope of the recovery from forward masking is steeper in NH listeners than in HI listeners, due to reduced cochlear nonlinearities with cochlear hearing loss (e.g., Ludvigsen, 1985; Oxenham and Moore, 1997). Oxenham and Moore (1997) and Derleth *et al.* (2001) modeled the effects of hearing loss on recovery from forward masking and showed that changes in forward masking can be predicted solely by introducing a loss of cochlear nonlinearities, affecting the slope of recovery, while keeping the duration of recovery constant. Thus, the time constant of recovery from forward masking, or the time course over which listeners' forward-masked thresholds return to quiet threshold levels, is not expected to be largely affected by hearing loss (e.g., Oxenham and Bacon, 2003).

When considering the known effects of hearing loss on recovery from forward masking, differences in cochlear nonlinearities are not consistent with the similarities in recovery for NH and HI listeners observed in Svec *et al.* (2015^a). However, more information is needed about the slope and time constant, or time course, of recovery for forward maskers that vary in inherent envelope fluctuations.

B. Effects of Forward Masker Bandwidth

Masker bandwidth may be an important variable for understanding the masking effects of inherent envelope fluctuations. Although masker bandwidth did not explain differences in forward masking for NH and HI listeners in a previous study (Svec *et al.*, 2015^a), forward-masked thresholds for maskers with different bandwidths at a range of masker-probe delays may provide additional information related to the theoretical implications posited by Hartmann and Pumplin (1988) about the relationships between

the temporal envelopes of GN and LFN as a function of bandwidth. The results of Hartmann and Pumplin (1988) suggested that the temporal envelope of LFN is maximally flat (e.g., minimal fluctuations) when the bandwidth of the masker is within the boundaries of a critical band. As the bandwidth of LFN increases, approaching or exceeding a critical band, fluctuations will likely be introduced to the temporal envelope of the noise by being passed through adjacent auditory filters. The increased effective envelope fluctuations of LFN, presumably related to the filtering process of the peripheral auditory system, make it more similar to the temporal envelope of GN with a comparable bandwidth. Kohlrausch *et al.* (1997) examined the effects of inherent envelope fluctuations by measuring masked thresholds for pure tones in the presence of either GN or LFN simultaneous maskers that varied in bandwidth; they found that GN produced more masking than LFN for a fairly wide range of masker bandwidths at both 1000 and 10,000 Hz. However, a masker bandwidth of 25-50 Hz produced the greatest difference in masked thresholds between GN and LFN at 1000 Hz, suggesting that a masker bandwidth near one-third an equivalent rectangular bandwidth (ERB, Glasberg and Moore, 1990) may reveal the maximal additional amount of masking yielded by GN as compared to LFN.

In the previous study, Svec *et al.* (2015^a) showed that a 1/3 ERB GN forward masker not only produced more masking than a 1/3 ERB LFN forward masker, but that a greater difference (GN>LFN) was observed for the 1/3 ERB maskers than a slightly broader bandwidth masker of 1 ERB. These results are in good agreement with those of Kohlrausch *et al.* (1997), which used simultaneous maskers in NH listeners only;

however, for the results of Svec *et al.* (2015^a), this effect of masker bandwidth was unexpectedly similar for NH and HI listeners at a short masker-probe delay of 25 ms. Whether or not comparable bandwidth effects will be observed at longer masker-probe delays was investigated in the current study.

C. Research Questions

The current study was designed to assess effects of hearing loss on the slopes of recovery, and the amount of recovery, from four forward maskers that varied in inherent envelope fluctuations: GN or LFN, with 1 or 1/3 ERBs. Forward-masked thresholds were measured at 2000 and 4000 Hz, for masker-probe delays of 25, 50, and 75 ms, for NH and HI adults. Slopes of recovery from forward masking for each masker type and bandwidth were estimated by computing the slope of the function relating masked threshold to masker-probe delay. Additional masking due to inherent envelope fluctuations was estimated by comparing forward-masked thresholds for maskers with maximal fluctuations (GN) to those with minimal fluctuations (LFN). This method provided estimates of masking yielded by inherent envelope fluctuations beyond that yielded by forward masking alone at each masker-probe delay.

Previous work (Svec *et al.*, 2015^a) led to two new research questions: 1) Do slopes of recovery from these variably fluctuating forward maskers differ for NH and HI listeners?, and 2) Does additional masking due to inherent envelope fluctuations differ for NH and HI listeners and, if so, do these differences vary with masker-probe delay? Based on previous results (e.g., Oxenham and Bacon, 2003; Oxenham and Moore, 1997), we predicted that slopes of recovery from forward masking would be shallower for HI than

NH listeners, and differences in slopes between NH and HI listeners would be larger at 4000 than 2000 Hz, due to greater hearing loss. Because disruption due to inherent envelope fluctuations may occur for a longer time course for HI than NH listeners based on previous results from forward-masked modulation detection interference (Koopman *et al.*, 2008), we predicted that the increase in masked thresholds with higher fluctuation maskers would be greater for HI than NH listeners at longer masker-probe delays.

II. METHODS

A. Participants

For the 4000 Hz conditions, nineteen adult listeners (6 males, 13 females) participated in this experiment. For the NH adults (n=9, age 19-35 years), pure-tone thresholds in the test ear were ≤ 20 dB HL at audiometric frequencies from 250 to 8000 Hz (ANSI, 2004). For HI adults (n=10, age 60-89 years), pure-tone thresholds were < 50 dB HL at 250, 500, and 1000 Hz, between 25 and 60 dB HL at 2000 and 4000 Hz, and between 25 and 70 dB HL at 8000 Hz. Based on the absence of age-related differences in forward masking (e.g., Svec *et al.*, 2015^a; Dubno *et al.*, 2003), we did not include a group of older normal-hearing participants in the current study. One NH and two HI listeners that completed the 4000 Hz conditions did not complete the 2000 Hz conditions. HI listeners with conductive or mixed hearing losses were not eligible for participation. Listeners were compensated for their participation.

The left panel of *Fig. 3.1* contains mean (filled symbols) and individual (dashed lines) pure-tone thresholds in the test ear measured in dB HL (ANSI, 2004) and

converted to dB SPL for the two groups of listeners. For NH listeners, the better ear was chosen as the test ear for all listeners. For the HI listeners, if both ears met the inclusion criteria, the ear with better thresholds at 2000 and 4000 Hz was chosen for testing. If thresholds were identical at 2000 and 4000 Hz, the right ear was chosen for testing. The center and right panels of *Fig. 3.1* contain mean (filled symbols) and individual (open symbols) pure-tone thresholds (in dB SPL) in the test ear for the 10-ms, 2000-Hz (center) and 4000-Hz (right) probes. Mean probe thresholds at 2000 Hz were 23.2 and 50.1 dB SPL for the NH and HI groups, respectively. At 4000 Hz, mean probe thresholds were 20.4 and 62.2 dB SPL for the NH and HI groups, respectively.

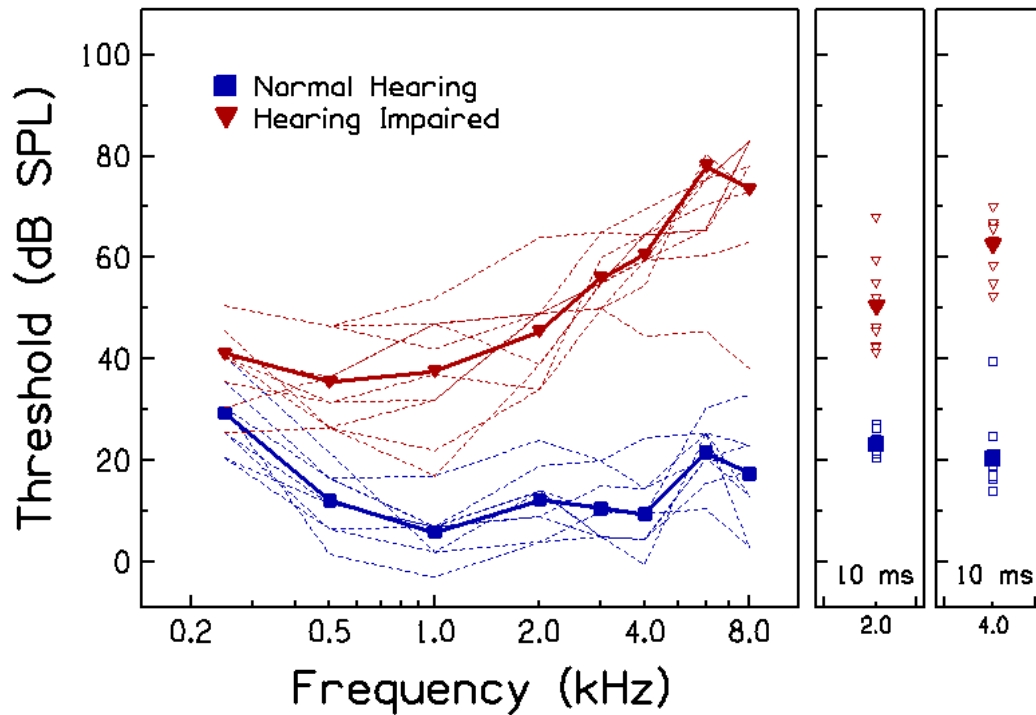


FIG. 3.1. Mean (filled symbols) and individual (dashed lines) pure-tone thresholds measured (in dB HL, converted to dB SPL) in the test ear for 250-ms signals for NH and HI participants (left). Mean (filled) and individual (open) pure-tone thresholds (in dB SPL) in the test ear

for the 10-ms probe for two groups at 2 kHz (middle) and 4 kHz (right).

B. Apparatus and Stimuli

Each signal was generated at a sampling rate of 44,100 Hz, produced via a Matlab script file matched with a Lynx TWO-B soundcard and a DAC1 D/A converter, and presented through a Tucker-Davis Technologies (TDT) HB6 headphone buffer driving a Sennheiser HD650 circumaural earphone. The duration of both the 2000- and 4000-Hz pure-tone probes was 10 ms, including 5-ms raised cosine onset and offset ramps. Each of eight 400-ms maskers, including 5-ms raised cosine onset and offset ramps, was centered at either 2000 or 4000 Hz: (a) GN with a bandwidth of 1 ERB (241 Hz, or 463 Hz) and cutoff frequencies of 1883 and 2124 Hz, or 3775 and 4238 Hz; (b) GN with a bandwidth of 1/3 ERB (80 Hz, or 154 Hz) and cutoff frequencies of 1960 and 2040 Hz, or 3924 and 4078 Hz, and (c) four LFN maskers with bandwidths and cutoff frequencies identical to those of the GN maskers. Both the GN and LFN maskers were generated following a procedure described by Buss *et al.* (2006), originally adapted from the method for creating LFN developed by Kohlrausch *et al.* (1997). A band of GN centered at either 2000 or 4000 Hz for each corresponding bandwidth (1 or 1/3 ERB) was divided by the Hilbert envelope in the time domain and then multiplied by the original spectrum in the frequency domain. For the LFN, the multiplication was repeated 10 times, resulting in a temporal envelope with minimal inherent fluctuations.

Crest factors, or the ratios between peak amplitude and the root-mean-square (rms) amplitude within the temporal envelope of the waveform (e.g., Hartmann and

Pumplin, 1988), were calculated to provide an estimate of the power in the peaks of the amplitude fluctuations compared to the overall energy of the noise. For our experimental conditions, crest factors were calculated for 100 noise samples generated for each of the eight maskers; mean crest factors and standard deviations were computed. As expected, mean crest factors for both center frequencies were higher for GN (1 ERB: 11.4; 1/3 ERB: 10.6) than LFN (1 ERB: 4.5; 1/3 ERB: 4.4). In addition, standard deviations were much higher for GN (1 ERB: 0.77; 1/3 ERB: 0.77) than LFN (1 ERB: 0.12; 1/3 ERB: 0.16).

Initiation of the masker occurred 50 ms after the beginning of the interval. The probe was presented 25, 50, or 75 ms after the offset of the masker. The overall level of the masker was fixed at 80 dB SPL. See Svec *et al.* (2015^a, *Fig. 3.2*) for a schematic of the waveforms for the probe, 1 ERB GN, and 1 ERB LFN. A computer monitor displayed the timing of signal presentations. A touchscreen interface was used to record participant responses inside a double-walled, sound-treated booth.

C. Procedures

Detection thresholds for the 10-ms probe at either 2000 or 4000 Hz were measured in quiet using a three-interval forced choice (3IFC) two-up, one-down adaptive psychophysical procedure tracking 70.7% correct on the psychometric function (Levitt, 1971). Each block ceased after 12 reversals. Each trial contained three 600-ms observation intervals separated by a 500-ms inter-stimulus interval. Only one of the three intervals contained the probe. Participants received feedback for whether or not they chose the correct interval on a given trial. The probe starting level was 50 dB SPL for NH

listeners and 80 dB SPL for HI listeners. Initial step size was 5 dB and changed to 2 dB after the first two reversals. Thresholds were calculated as mean probe level (dB SPL) for the final 8 reversals following completion of a given block. Mean thresholds for each condition were based on at least three blocks. If the standard deviation of a given block exceeded 5 dB, a fourth block was obtained, and the mean of all four threshold estimates became the final probe threshold. The right panel of *Fig. 3.1* displays probe thresholds measured in quiet. A very similar procedure, aside from probe starting levels, was used to measure masked thresholds by holding the masker level constant at 80 dB SPL and varying the probe level adaptively.

A training session was completed before data collection commenced to familiarize listeners with the GN and LFN maskers. During training, the starting level for the probe was 80 dB SPL for the NH listeners and 95 dB SPL for the HI listeners. Training for a given condition ceased once the participant's performance reached a standard deviation of <5 dB within a block. Once forward masking data collection began, starting levels for the probe were set to 20 dB SL re: masked threshold determined during training.

The testing conditions were blocked by masker bandwidth (1 ERB or 1/3 ERB), masker type (GN or LFN), and masker-probe delay (25, 50, or 75 ms), and randomized by a number assigned to each of the 24 conditions. Over multiple visits, testing did not exceed ten hours, including informed consent, audiometry, training, and data collection. Frequent breaks were offered to participants.

A repeated-measures analysis of variance (ANOVA) using the general linear model in SPSS was used to assess the effects of masker type (GN, LFN), bandwidth (1/3 ERB, 1 ERB), masker-probe delay (25, 50, 75 ms), and participant group (NH, HI) on forward-masked thresholds. Differences were considered significant with $p < 0.05$. Mauchly's test of sphericity suggested that the assumption of equal variance was not violated. The hypotheses predicted significant main effects for all four factors, and significant interactions between masker type, masker bandwidth, masker-probe delay, and participant group. Regression slopes and masked threshold differences for NH and HI listeners were analyzed using one-tailed, two sample t-tests with unequal variance assumed. The association between slopes of recovery from LFN or GN maskers and magnitude of hearing loss (threshold for the probe in quiet) were assessed using correlational analyses.

III. RESULTS

A. Quiet Thresholds

Quiet thresholds for the 10-ms pure-tone probe at 2000 and 4000 Hz were not significantly different for NH listeners ($p > 0.05$), but thresholds were significantly higher at 4000 Hz than 2000 Hz for HI listeners ($p < 0.05$) (see *Fig. 3.1*). In addition, quiet thresholds for the 10-ms pure-tone probe were significantly higher for HI than NH listeners at both 2000 ($p < 0.001$) and 4000 Hz ($p < 0.001$).

B. Masked Thresholds

Masked thresholds for all maskers at all masker-probe delays were significantly higher for HI than NH listeners for both 4000 Hz [$F(1, 17) = 123.2, p < 0.001$] and 2000 Hz [$F(1, 14) = 54.4, p < 0.001$] (see *Fig. 3.2*).

At 4000 Hz, a significant two-way interaction of listener group and masker-probe delay [$F(2, 34) = 31.87, p < 0.001$], as well as a three-way interaction of listener group, masker-probe delay, and masker type [$F(2, 34) = 3.82, p < 0.05$] were observed. Post-hoc tests for planned comparisons revealed that, for HI listeners, masked thresholds for GN were greater than masked thresholds for LFN at masker-probe delays of 25 and 50 ms for both masker bandwidths ($p < 0.05$). In contrast, for NH listeners, masked thresholds for 1/3 ERB GN were greater than masked thresholds for 1/3 ERB LFN only at a masker-probe delay of 25 ms ($p < 0.05$).

At 2000 Hz, a significant two-way interaction of masker-probe delay and listener group [$F(2, 28) = 3.941, p < 0.05$], as well as a three-way interaction for masker type, masker bandwidth, and masker-probe delay [$F(2, 28) = 0.355, p < 0.05$] was observed. Post-hoc tests for planned comparisons revealed that GN resulted in greater masking than LFN only at a masker-probe delay of 25 ms for both NH ($p < 0.05$) and HI ($p < 0.05$) listeners. Similarly, differences between narrower (1/3 ERB) and wider (1 ERB) masker bandwidths were observed only at a masker-probe delay of 25 ms for both NH ($p < 0.05$) and HI ($p < 0.05$) listeners.

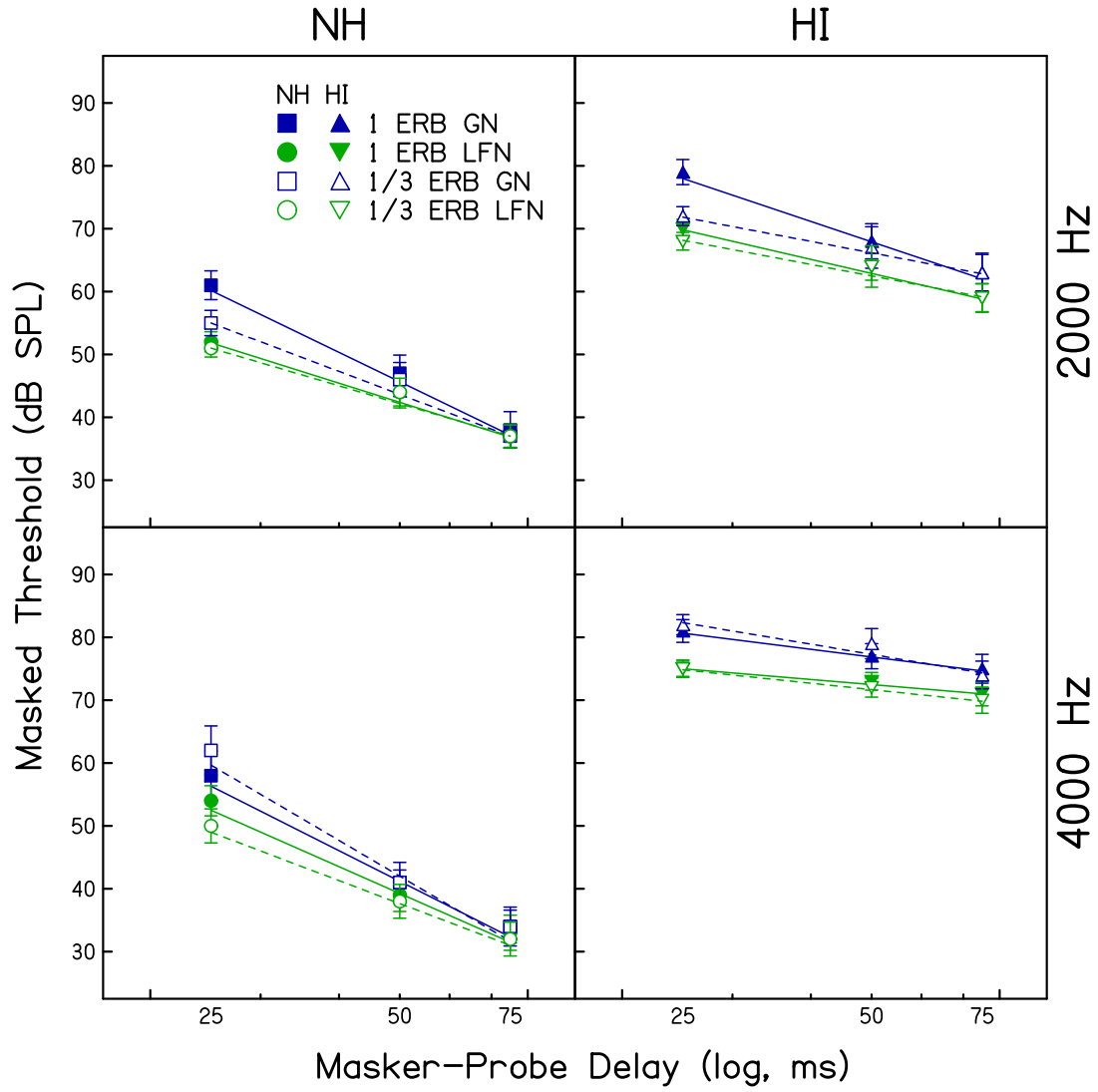


FIG. 3.2. Mean (± 1 SE) forward-masked thresholds (in dB SPL) for two masker bandwidths (1 ERB – filled, 1/3 ERB – open) and two masker types (GN – squares and triangles, LFN – circles and inverted triangles) for NH (left panels) and HI (right panels) listeners.

C. Masked Threshold Differences (GN-LFN)

For 4000 Hz, additional masking for the GN, relative to the LFN maskers, was significantly larger for HI than NH listeners for both masker bandwidths at the 50- and

75-ms masker-probe delays ($p < 0.05$, $p < 0.001$; respectively), but not for the 25-ms delay ($p > 0.05$) (see *Fig. 3.3*).

For 2000 Hz, masked threshold differences (GN-LFN) did not differ significantly for NH and HI listeners ($p > 0.05$), although a trend was observed suggesting larger differences for HI than NH listeners at the longest masker-probe delay ($p = 0.05$).

Because masked threshold differences between GN and LFN maskers were observed for HI listeners at the longest masker-probe delays for 4000 Hz, these findings suggest that the masking effects from inherent envelope fluctuations are larger and persist for a longer time course for HI listeners in regions with greater hearing loss than for NH listeners. These findings also suggest that the additional masking due to inherent masker envelope fluctuations for HI listeners is not significantly different from NH listeners in a region with better hearing, namely 2000 Hz.

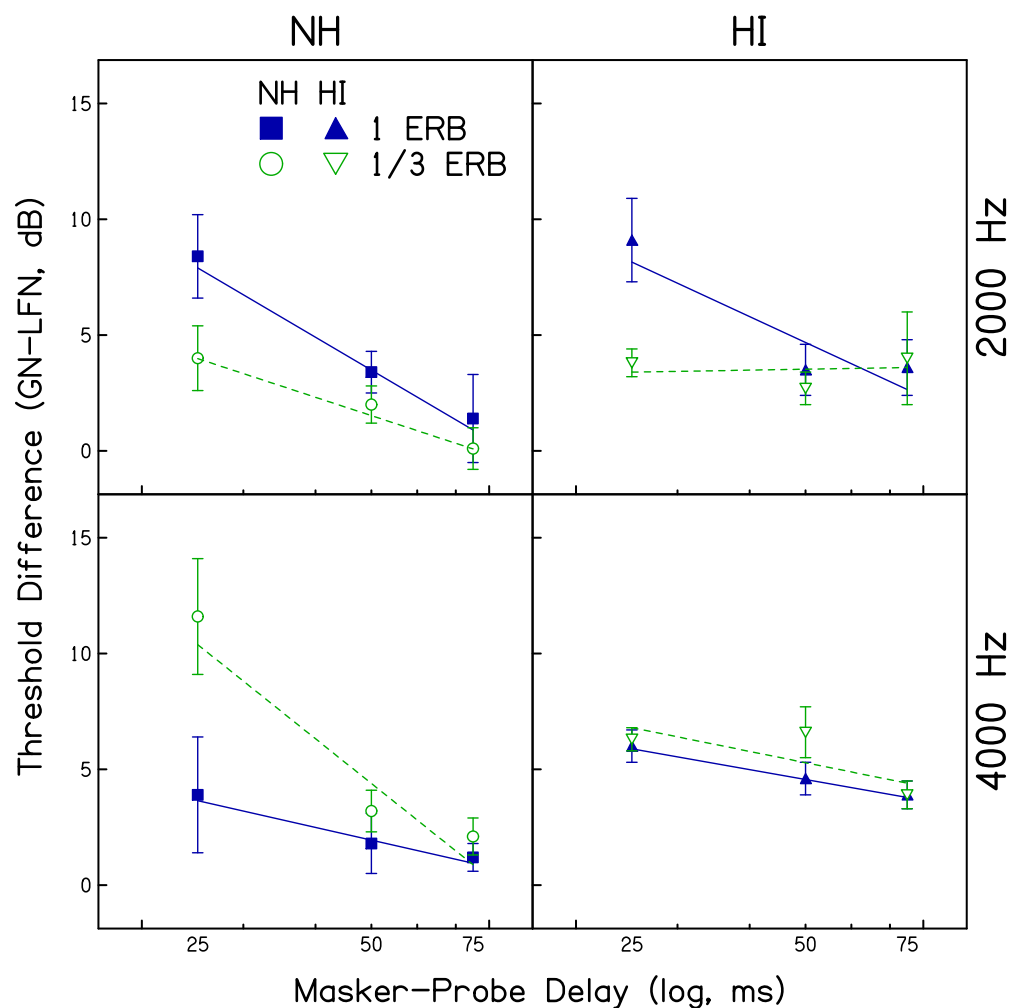


FIG. 3.3. Mean (± 1 SE) masked threshold differences (in dB) for two masker bandwidths (1 ERB – filled, 1/3 ERB - open) for NH listeners (left) and HI listeners (right).

D. Associations Between Recovery Slopes and Hearing Loss

For all LFN maskers at both 2000 and 4000 Hz, slopes of recovery were significantly shallower for HI than NH listeners ($p < 0.001$), consistent with previous findings (e.g., Oxenham and Bacon, 2003). Similar to LFN, for all GN maskers at both

2000 and 4000 Hz, slopes of recovery were significantly shallower for HI listeners than NH listeners (1 ERB GN: $p < 0.05$; all other GN maskers: $p < 0.001$) (see *Table 3.1*).

For NH listeners, slopes of recovery were not significantly correlated with probe thresholds in quiet for any masker ($p > 0.05$) (see *Fig. 3.4* and *Table 3.2*). This is expected due to the narrow range of quiet thresholds for the NH participants. For HI listeners, slopes of recovery were positively correlated with probe thresholds for narrower bandwidth (1/3 ERB) maskers at 4000 Hz (GN: $r = 0.71$, $p < 0.05$) and at 2000 Hz (GN: $r = 0.81$, $p < 0.05$; and LFN: $r = 0.78$, $p < 0.05$). Therefore, as hearing loss at the probe frequency increased for HI listeners, slopes of recovery functions became shallower, primarily for maskers with maximal inherent envelope fluctuations (e.g., 1/3 ERB GN).

SLOPES						
Frequency	Bandwidth	Type	NH	SE	HI	SE
2000 Hz	1 ERB	GN	-0.46	0.05	-0.32	0.04
		LFN	-0.30	0.03	-0.22	0.03
	1/3 ERB	GN	-0.36	0.03	-0.18	0.03
		LFN	-0.28	0.03	-0.18	0.03
4000 Hz	1 ERB	GN	-0.48	0.08	-0.12	0.02
		LFN	-0.42	0.05	-0.08	0.02
	1/3 ERB	GN	-0.56	0.08	-0.16	0.02
		LFN	-0.36	0.05	-0.10	0.03

TABLE 3.1. Mean (± 1 SE) slopes of recovery, calculated from forward-masked thresholds at 2000 and 4000 Hz probes for GN and LFN maskers at three masker-probe delays (25, 50, 75 ms) for NH and HI listeners.

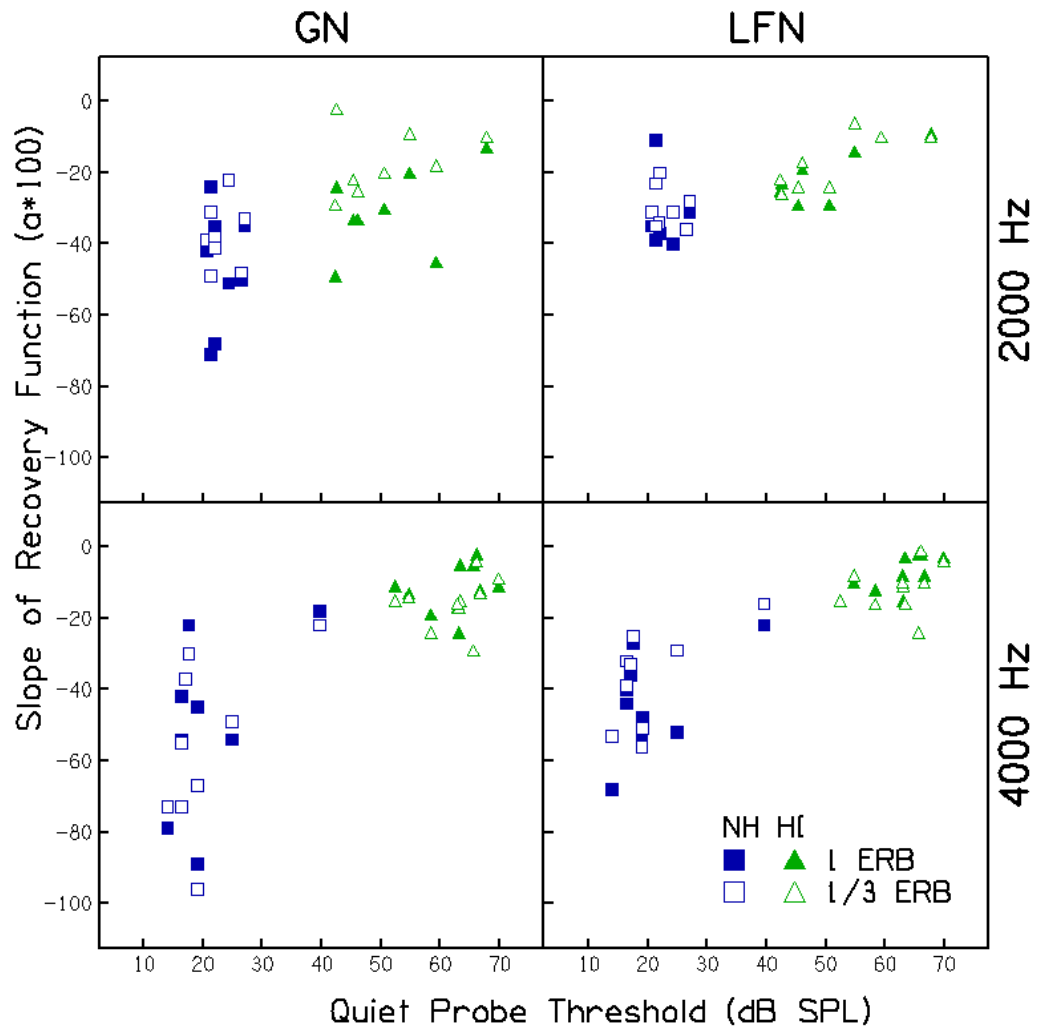


FIG. 3.4. Slopes ($a \cdot 100$) of recovery functions plotted against quiet probe thresholds (in dB SPL) for two masker bandwidths (1 ERB – filled, 1/3 ERB – open) and two masker types (GN – right, LFN – left) at 2000 Hz (top) and 4000 Hz (bottom) for NH (squares) and HI (triangles) listeners.

CORRELATIONS: SLOPES vs. PROBE THRESHOLDS					
Frequency	Bandwidth	Type	NH	HI	Overall
2000 Hz	1 ERB	GN	0.103	0.452	0.567*
		LFN	0.118	0.324	0.772**
	1/3 ERB	GN	-0.181	0.806*	0.726**
		LFN	-0.215	0.778*	0.801**
4000 Hz	1 ERB	GN	0.471	0.262	0.800**
		LFN	0.532	0.218	0.826**
	1/3 ERB	GN	0.533	0.705*	0.915**
		LFN	0.617	0.366	0.846**

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

TABLE 3.2. Correlations between recovery slope and quiet probe threshold for each bandwidth (1 ERB, 1/3 ERB) of GN and LFN for center frequencies of 2000 (top) and 4000 (bottom) Hz.

IV. DISCUSSION

A. Primary Findings

The current study revealed two primary differences between NH and HI listeners for recovery from forward maskers that varied in inherent envelope fluctuations. First, as predicted and as previously observed, slopes of recovery from forward masking were shallower for HI than NH listeners. In addition, this relationship between slopes and listener group was observed regardless of masker fluctuations and degree of hearing loss at the probe frequency.

Second, at 4000 Hz, additional masking attributed to inherent masker envelope fluctuations, or masked thresholds differences between GN and LFN, was significantly larger for HI than NH listeners at the two longer masker-probe delays. At the shortest

masker-probe delay, no significant differences in additional masking were observed between NH and HI listeners, which are in good agreement with the results from Svec *et al.* (2015^a). At 2000 Hz, no significant differences in additional masking were observed between NH and HI listeners at any masker-probe delay, suggesting that recovery from inherent envelope fluctuations may be more similar in this region where hearing thresholds were also more similar for NH and HI listeners.

B. Implications of Masking Due to Envelope Fluctuations and Slopes of Recovery

At 4000 Hz, a significant difference for HI listeners between masked thresholds for GN and LFN conditions at the longest masker-probe delay suggests that these listeners have not fully recovered from additional masking attributable to the inherent envelope fluctuations of the GN. Although shallower slopes of recovery from forward masking in HI listeners are predicted by reductions in cochlear nonlinearities, as stated previously, the time constant of recovery from forward masking is not expected to be affected by hearing loss. Given the similarities in the presumed effect of inherent envelope fluctuations for NH and HI listeners for at a short masker-probe delay and the differences in this effect between NH and HI listeners at a longer masker-probe delay, a mechanism other than loss of cochlear nonlinearities may be responsible for the change in the time course of recovery from inherent fluctuations for HI listeners.

Ludvigsen (1985) developed a model of recovery from forward masking for NH and HI listeners for both low- and high-level maskers that may have implications for the results from the current study. While the model is based on a fairly broad assumption that forward-masked thresholds return to quiet probe thresholds by a masker-probe delay of

200 ms regardless of the fixed masker level and degree of hearing loss, it provides a framework for describing forward masking effects as a function of masker level and masker-probe delay in NH and HI listeners. In the model, masked thresholds at a masker-probe delay of 3 ms (masker offset) for the low- and high-level maskers were set to be equivalent for NH and HI listeners, and recovery from both masker levels was assumed to be complete at a masker-probe delay of 200 ms. Slopes of recovery from both maskers were steeper for NH than HI listeners. At any masker-probe delay before convergence, there was a greater difference between the low- and high-level maskers for the HI than the NH listeners; however, masked thresholds for the low- and high-level maskers converged at the same masker-probe delay in both sets of listeners.

According to the model proposed by Ludvigsen, if the magnitude of masking attributed to inherent fluctuations were simply an increase in effective masker level leading to greater forward masking in the current study, functions defining recovery from GN and LFN for the NH and HI listeners would have converged at the same masker-probe delay. However, in contrast to predictions from Ludvigsen's model, for NH listeners in our study, GN and LFN functions converged relatively quickly (~50 ms), whereas for HI listeners, functions had not converged with a masker-probe delay of 75 ms.

From previous results (e.g., Oxenham and Bacon, 2003), we expect that recovery from forward masking will be shallower for HI than NH listeners. Moreover, if masked thresholds were related to recovery from forward masking alone, functions describing recovery from GN and LFN maskers should converge at the same masker-probe delay.

The masked threshold differences observed for GN and LFN in the current study suggest that a mechanism in addition to forward masking may also be contributing.

Because slopes of recovery from both GN and LFN at 2000 Hz, a region in which HI listeners had better hearing, were still significantly shallower for HI than NH listeners, we infer that even mild cochlear hearing loss affects slopes of recovery from forward masking for both masker types. In contrast, because differences in masked thresholds between highly fluctuating maskers (GN) and maskers with a flatter temporal envelope (LFN) were observed for HI listeners at the longest masker-probe delays at 4000 Hz, but not 2000 Hz, this suggests that the persistence of masking effects from inherent envelope fluctuations at a longer time course may increase with increasing hearing loss in a particular cochlear region.

One limitation of the current study is that the actual time constants of recovery, the duration over which listeners' forward-masked thresholds return to quiet threshold levels, were not measured. Consequently, differences in time constants between NH and HI listeners for recovery from inherent fluctuations cannot be directly compared.

C. Mechanisms of Forward Masking in the Audio and Modulation Frequency Domains

Although the mechanism in the auditory system that is responsible for the time constant of recovery from forward masking remains unclear, investigators have recently focused on a few possibilities. Nelson *et al.* (2009) recorded single-fiber responses in neurons of the inferior colliculus (IC) in marmosets to assess whether or not forward masking could be accounted for at the level of the mid-brain. Many individual cells

exhibited suppression comparable to the phenomenon of forward masking measured behaviorally in humans, leading the investigators to assert that, the auditory mechanism responsible for the time constant of recovery presumably precedes the IC in the afferent auditory pathway. While this is in good agreement with the assumption that the time constant for recovery is dependent on some combination of neural integration and adaptation occurring shortly after cochlear processing in the audio-frequency domain (Oxenham, 2001), the results of Wojtczak *et al.* (2011) suggest that this may not be the case when considering forward masking in the modulation frequency domain. They compared amplitude-modulated (AM) forward masking for behavioral results in human participants and physiological results in the IC neurons of rabbits. For a behavioral experiment in humans, they measured AM forward masking using pure-tone carriers, including a 40-Hz AM masker (150 ms) that was followed by a 40-Hz AM signal (50 ms). Behavioral results were in good agreement with those from Wojtczak and Viemeister (2005), which used broadband noise carriers instead of pure tones, suggesting that an AM forward masker can significantly elevate masked modulation detection thresholds for NH listeners with masker-signal delays as long as 210 ms. To compare these behavioral results to physiology, the authors measured very similar conditions in the IC neurons of rabbits. Comparisons revealed that, unlike forward masking in the audio-frequency domain, suppression at the level of the IC could not reasonably account for AM forward masking, suggesting that the mechanisms for recovery from the sequential modulation masking may arise from mechanisms central to the IC.

As previously mentioned, changes in the temporal envelope of the masker, such as those related to inherent envelope fluctuations, affect a listener's ability to take advantage of envelope-based detection cues related to the onset or offset of the probe, which may be comparable to effects of modulation masking. The magnitude and time course of recovery from inherent envelope fluctuations that are related to recovery from AM forward masking, in contrast to forward masking in the audio-frequency domain, would explain some of the results for our NH listeners. However, the time course and magnitude of recovery from AM forward masking for HI listeners remains unknown.

D. Listener Uncertainty

Considered in similar domains as “confusion effects” (Neff, 1986), the term “masker uncertainty” is often used when describing sources of masking associated with across-trial statistical variations of masker waveforms, leading to what we will call “listener uncertainty.” As mentioned, listener uncertainty is greater for GN than for LFN maskers due to variability of inherent fluctuations in the temporal envelope of the stimuli (Buss *et al.*, 2006; Eddins, 2001). Lutfi (1990) quantified this uncertainty and estimated that up to 22% of the amount of masking for tone-in-noise experiments (simultaneous and forward masking) may be due to this listener uncertainty. Although there was little reason to assume that the masker-probe delays used in the current study would elicit conventionally described “confusion effects,” we hypothesized that listener uncertainty due to inherent masker fluctuations may be reduced by presenting the listener with a robust diotic cue for the masker offset.

To determine the extent to which a diotic temporal cue would affect listener uncertainty in conditions where a substantial difference was observed between GN and LFN maskers, we presented a subset of listeners with binaural masking conditions that were designed to optimize detection of the probe. Diotic forward maskers (1/3 and 1 ERB, GN and LFN) centered at 4000 Hz were presented binaurally in conjunction with the identical monaural probe used in the previous experiment at a masker-probe delay of 25 ms to three of the NH listeners and three of the HI listeners who had participated in the previous portion of the current study. In addition, these same diotic forward maskers were presented to these HI listeners at a masker-probe delay of 75 ms, because substantial differences in masked thresholds between GN and LFN were still observed in these listeners at the longest masker-probe delay.

Overall, the diotic maskers reduced binaural masked thresholds relative to monaural masked thresholds by 13.5 to 15.1 dB for GN and 6.7 to 11.0 for LFN for the NH listeners. For HI listeners, binaural relative to monaural masked thresholds were reduced by 5.9 to 6.9 for GN and 1.5 to 1.8 for LFN at a masker-probe delay of 25 ms, and by 0.6 to 5.4 for GN and -2.0 to 0.6 for LFN at a masker-probe delay of 75 ms. As predicted, the binaural cue reduced differences between GN and LFN masked thresholds by 8.3 dB for 1/3 ERB and 2.5 dB for 1 ERB for NH listeners. For HI listeners, the binaural cue reduced differences between GN and LFN masked thresholds by 4.1 dB for 1/3 ERB and 5.4 dB for 1 ERB at a masker-probe delay of 25 ms, as well as by 2.3 dB for 1/3 ERB and 2.2 dB for 1 ERB at a masker-probe delay of 75 ms. These results suggest

that the envelope-based cue was likely disrupted by the greater inherent masker envelope fluctuations of GN than LFN in the monaural conditions.

While the “listener uncertainty” effect mirrors some of the attributes of confusion effects, it seems unlikely that a listener is “confusing” a masker and probe that are separated by 75 ms. More aptly, we are describing this effect as the “persistence of listener uncertainty,” suggesting that the disruption due to inherent masker envelope fluctuations persists in HI listeners for a greater duration than in NH listeners. Measuring the amount of AM forward masking contributing to the persistence of these masking effects will help isolate the contributions of modulation masking and listener uncertainty for the monaural conditions.

E. Implications and Future Directions

Because inherent envelope fluctuations of a forward masker yielded relatively more masking at longer masker-probe delays for HI than NH listeners, the contribution of AM forward masking may be relevant. This persistence of the effect of inherent envelope fluctuations may also differentially affect the detection of signals other than pure tones, such as detecting modulation within a signal after the offset of the masker. By using GN and LFN AM forward maskers in a frequency-specific place, we can continue to explore questions related to AM forward masking observed for NH listeners (Wojtczak and Viemeister, 2005; Wojtczak *et al.*, 2011) for listeners with hearing loss. For example, it is not known if AM forward masking at longer masker-signal delays will be larger for HI than NH listeners. If so, the contribution of AM forward masking and effects of inherent

envelope fluctuations may be relevant for interpreting differences between NH and HI listeners for speech recognition presented in amplitude-modulated noise.

V. CONCLUSIONS

- 1) As predicted, slopes of recovery from forward masking were shallower for HI than NH listeners, regardless of masker fluctuations and degree of hearing loss at the probe frequency.
- 2) Additional masking at 4000 Hz attributed to inherent envelope fluctuations was significantly larger for HI than NH listeners at the two longer masker-probe delays, suggesting that some persistence of the masking effects from inherent envelope fluctuations occurs for a longer time course in a region of greater hearing loss. No significant differences in additional masking between NH and HI listeners were observed at any masker-probe delay for 2000 Hz, suggesting that recovery from inherent envelope fluctuations is more similar for the two groups in this region where their quiet thresholds were also more similar.
- 3) A binaural cue associated with a diotic forward masker elicited a reduction in the differences between GN and LFN masked thresholds for a subset of listeners, suggesting that listener uncertainty persists over a longer time course after the offset of a masker for HI than for NH listeners.

CHAPTER 4: AMPLITUDE-MODULATED FORWARD MASKING IN LISTENERS WITH NORMAL AND IMPAIRED HEARING

I. INTRODUCTION

A. Background

In a previous study (Svec *et al.*, 2015^b), excess forward masking due to inherent masker envelope fluctuations was larger for HI than NH listeners at masker-probe delays of 50 and 75 ms. Time constants for recovery from forward masking have been shown to be similar for NH and HI listeners (e.g., Oxenham and Bacon, 2003), yet the masking effects of inherent envelope fluctuations persisted for a greater amount of time for HI than NH listeners, at least in regions of hearing loss. These results suggest that some mechanism other than forward masking alone is likely contributing to the differences between NH and HI listeners at longer masker-probe delays. This masking persistence could have implications for understanding additional masking that may occur with hearing loss, especially related to the detection of low-level signals in inherently fluctuating background noise.

Possible explanations might include that the persistence, or duration, of listener uncertainty is greater for HI than NH listeners. Richards *et al.* (2004) found that, for NH listeners, random variations in a complex masker led to increased listener uncertainty resulting in increased masked thresholds, and that presenting a copy of the masker before each stimulus interval provided a cue that reduced masked thresholds. For NH listeners in the forward masking domain, “confusion” between a narrowband masker and a sinusoidal

probe that are separated by brief masker-probe delays (< 20 ms) has been reduced by additionally presenting a copy of the masker in the contralateral ear. The diotic presentation effectively centers the auditory image of the masker in the listener's head, while the image of probe remains in the test ear (Neff, 1986). Although this confusion has primarily been attributed to central factors, unaffected by changes in peripheral processing, greater decay in forward masking would likely be observed when peripheral compression is intact. Therefore, changes in peripheral compression due to hearing loss may play a role in the degree of confusion associated with central processing as the masker-probe delay is increased. The results of Svec *et al.* (2015^b) revealed that the binaural cue from a diotic forward masker elicited a significant reduction in threshold differences between maskers with maximal vs. minimal inherent envelope fluctuations at a masker-probe delay of 75 ms for HI listeners. In that study, however, approximately half of the additional masking attributable to inherent envelope fluctuations was still observed for HI listeners after presenting a binaural cue. This finding suggests that listener uncertainty related to temporal complexities of the masker envelope persists over a longer time course for HI than for NH listeners. Therefore, a source other than listener uncertainty is likely contributing to this additional residual masking.

It is plausible that HI listeners may be more susceptible than NH listeners to the sequential effects of modulations in a masker envelope. Svec *et al.* (2015^b) speculated that sequential modulation masking, or amplitude-modulated (AM) forward masking, may be contributing to some of the observed differences between forward maskers which have maximal or minimal inherent envelope fluctuations. If listeners were attending to a

change in the temporal envelope of the stimuli, namely the onset or offset of the probe following the offset of the masker, and these envelope-based detection cues were obscured by masker envelope fluctuations, then these disruptions may be partially related to AM forward masking. Wojtczak and Viemeister (2005) initially revealed the effect described as “AM forward masking,” by showing that masked modulation detection thresholds (MDTs) improved with increasing masker-signal delays when an AM masker temporally preceded an AM signal, which were both imposed upon a broadband carrier. Although the authors only tested NH listeners, increases in sequential modulation detection interference for HI relative to NH listeners have been previously observed (Koopman *et al.*, 2008).

Therefore, the differences in forward masking between NH and HI listeners due to inherent masker envelope fluctuations may be attributed to some combination of AM forward masking and the persistence of listener uncertainty. The magnitude of listener uncertainty has been quantified by examining differences in masked thresholds for the monaural and diotic conditions from Svec *et al.* (2015^b). The purpose of the current study is to compare AM forward masking for listeners with and without hearing loss.

B. Modulation Detection and Modulation Masking

Previous studies have observed similar simultaneous MDTs for NH and HI listeners. Moore and Glasberg (2001) measured unmasked MDTs for both NH and HI listeners for a 5000-Hz pure-tone carrier amplitude modulated at 40 Hz and presented at 80 - 90 dB SPL. Results suggested MDTs were comparable for NH (~ - 20 dB) and HI (~ -15 to -25 dB) listeners. A similar study using octave-band noise carriers, as opposed to

pure tones, found that listeners with unilateral hearing loss had very similar unmasked MDTs when compared between their normal and impaired ears (Moore *et al.*, 1992). These results suggest that temporal resolution determined by measuring unmasked MDTs is not largely affected by hearing loss.

Other studies have considered differences in simultaneous modulation masking, or an increase in MDTs observed for modulated masker conditions relative to unmodulated masker conditions (e.g., Bacon and Grantham, 1989). Multiple investigators have found little difference between NH and HI listeners when modulation rates of the masker and the signal are relatively high (e.g., Takahashi and Bacon, 1992; Lorenzi *et al.*, 1997). However, it remains unknown whether or not AM forward masking, when the masker precedes the signal in time, is increased for HI relative to that for NH listeners at longer masker-signal delays. If unmasked MDTs and simultaneously masked MDTs are similar for NH and HI listeners, this should provide a good framework for assessing differences in the amount of AM forward masking between NH and HI listeners as the masker and signal are separated in time.

C. Research Questions

For these reasons, we measured AM forward masking for both NH and HI listeners at 4000 and 1000 Hz, using continuous and non-continuous masker and signal carriers. Because inherent fluctuations of a masker envelope can influence the amount of forward masking across masker-signal delays differently for NH and HI listeners (Svec *et al.*, 2015^b), we initially used a low-fluctuation noise (LFN; Hartmann and Pumplin, 1988) carrier for the “continuous carrier” conditions to examine the sole masking contribution

of deliberately imposed 40 Hz masker modulations. Each carrier had a bandwidth of 1/3 equivalent rectangular bandwidth (ERB; Glasberg and Moore, 1990) of a given center frequency to optimize the flatness of the temporal envelope (e.g., Kohlrausch *et al.*, 1997).

To be able to compare the amount of AM forward masking yielded by an unmodulated LFN masker, unmodulated Gaussian noise (GN) masker, and an amplitude-modulated LFN masker, additional conditions were included using a “non-continuous carrier,” as well.

D. Hypotheses

Based on previous results (Koopman *et al.*, 2008; Svec *et al.*, 2015^b), we hypothesized that, in the continuous carrier conditions, AM forward-masked MDTs would be elevated at longer masker-signal delays for HI relative to NH listeners at 4000 Hz, suggesting that AM forward masking may be contributing to excess disruptions experienced by HI listeners after the offset of a masker in the modulation masking domain. For the 1000 Hz carrier, we hypothesized that forward-masked MDTs for HI listeners would be more similar to NH listeners, due to less hearing loss at 1000 Hz in HI listeners.

In the non-continuous carrier conditions, we hypothesized that unmodulated LFN conditions would yield less AM forward masking than the unmodulated GN. We also hypothesized, based on the results of Svec *et al.*, (2015^b), that the amplitude-modulated LFN and unmodulated GN would yield more AM forward masking for the HI than NH listeners.

II. METHODS

A. Participants

Fourteen adult listeners (6 males, 8 females) participated in this experiment. For the NH listeners ($n=7$, age: 19–35 yr), pure-tone thresholds in the test ear were ≤ 20 dB hearing level (HL) at audiometric frequencies from 250 to 8000 Hz (ANSI, 2004). For HI listeners ($n=7$, age: 59–79 yr), pure-tone thresholds were < 50 dB HL at 250, 500, and 1000 Hz, between 25 and 60 dB HL at 2000 and 4000 Hz, and between 25 and 70 dB HL at 8000 Hz. Listeners with a conductive component to their hearing loss were not eligible for participation. Listeners were compensated for their participation.

Fig. 4.1 contains mean (filled symbols) and individual (dashed lines) pure-tone thresholds in the test ear for the two groups of listeners, measured in dB HL (ANSI, 2004) and converted to dB SPL. For the NH listeners, the test ear was chosen based on the best thresholds at 1000 and 4000 Hz. For the HI listeners, if both ears met the inclusion criteria, the ear with a better threshold at 4000 Hz was chosen for testing.

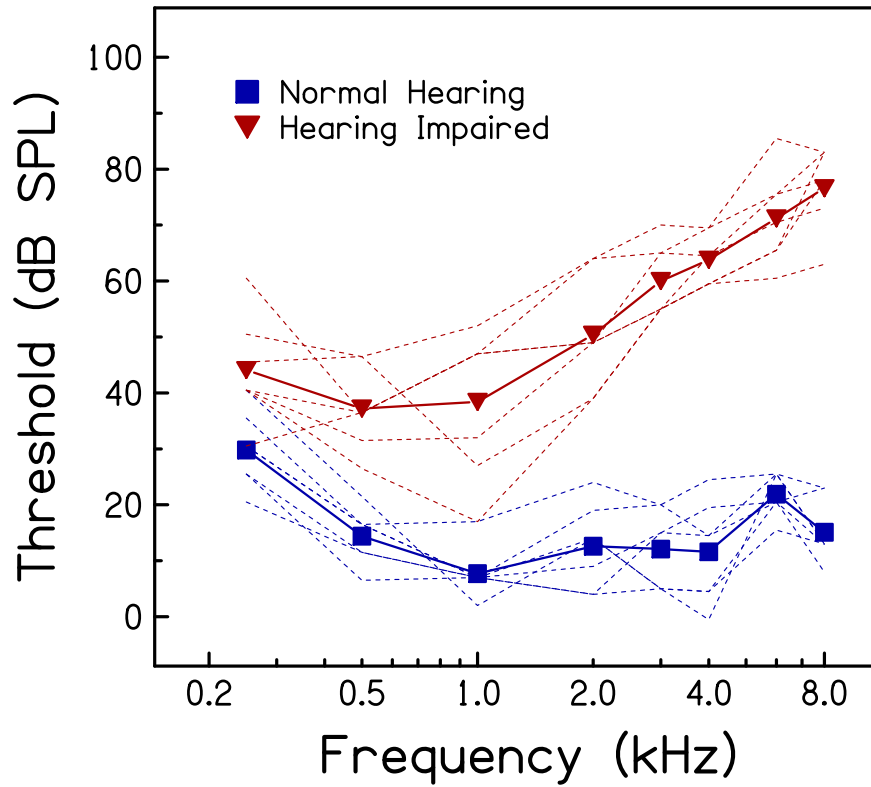


FIG. 4.1. Mean (filled symbols) and individual (dashed lines) pure-tone thresholds measured (in dB HL, converted to dB SPL) in the test ear for ~250-ms signals for NH and HI participants.

B. Apparatus & Stimuli

i. Continuous Carrier Conditions

The carrier (see *Fig. 4.2*) was 1/3 ERB LFN centered at either 4000 Hz (3924-4077 Hz) or 1000 Hz (978-1022 Hz). To generate the LFN carrier, a band of GN centered at either 4000 or 1000 Hz was divided in the time domain by the Hilbert envelope and bandpass filtered into the original spectral region (463 Hz- and 44 Hz-wide bands). This sequence of operations was repeated 20 times. The signal consisted of a 50-ms segment of 40-Hz sinusoidal amplitude modulation (SAM) imposed on the 500-ms noise carrier, including 5-ms raised-cosine onset/offset ramps. The maskers consisted of 150-

ms segments of 40-Hz SAM imposed on the same 500-ms noise carrier that contained the signal and began with the onset of the carrier. The onset of the signal temporally succeeded the offset of the masker, after masker-probe delays of 50, 100, or 200 ms. Carriers were fixed at 80 dB SPL. Modulation depth for the masker was fixed at 0 dB (20 log m, m = modulation index). Both masker and signal modulations began at 0-rad (sine) phase.

Continuous Carrier Conditions

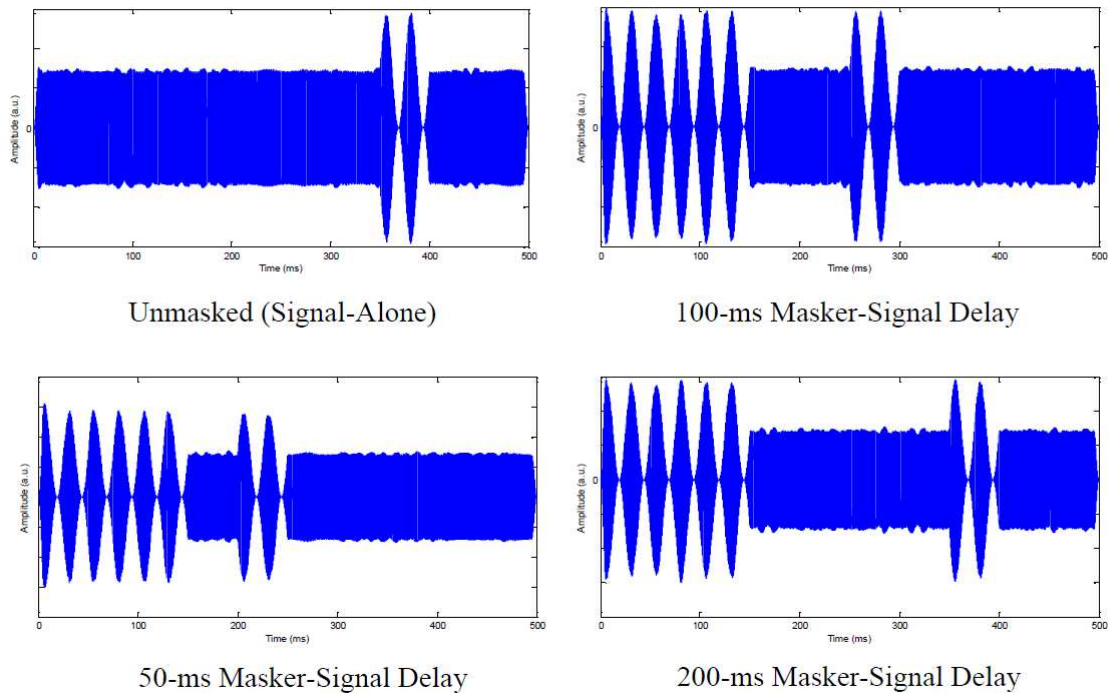


FIG. 4.2. Waveforms showing 500-ms low-fluctuation noise (LFN) carriers for the unmasked (top left) and masked conditions. The separation of the 150-ms 40 Hz AM masker from the 50-ms 40 Hz AM signal is shown at masker-signal delays of 50 (bottom left), 100 (top right), and 200 (bottom right) ms.

ii. Non-Continuous Carrier Conditions

As in the previously described continuous carrier conditions, the signal carrier for the non-continuous carrier conditions (see *Fig. 4.3*) was 1/3 ERB LFN centered at either 4000 Hz (3924-4077 Hz) or 1000 Hz (978-1022 Hz). Unlike the previous conditions, the carrier was gated on and off with the AM signal, resulting in a 50-ms segment of 40-Hz SAM imposed on a 50-ms carrier, including 5-ms raised-cosine onset/offset ramps. The 150-ms masker noise carrier was gated on and off with the 150-ms AM masker, including 5-ms raised-cosine onset/offset ramps. Masker-probe delay was fixed at 200 ms for each masker condition, which contained silence, as opposed to a continuation of the carrier. Aside from an unmasked condition (signal-alone), three masker conditions were presented to listeners using identical adaptive 3IFC procedures to those previously described to measure forward-masked MDTs: 1) Unmodulated LFN (U-LFN); 2) Unmodulated GN (U-GN); and 3) 40 Hz amplitude-modulated LFN (AM-LFN).

Non-Continuous Carrier Conditions

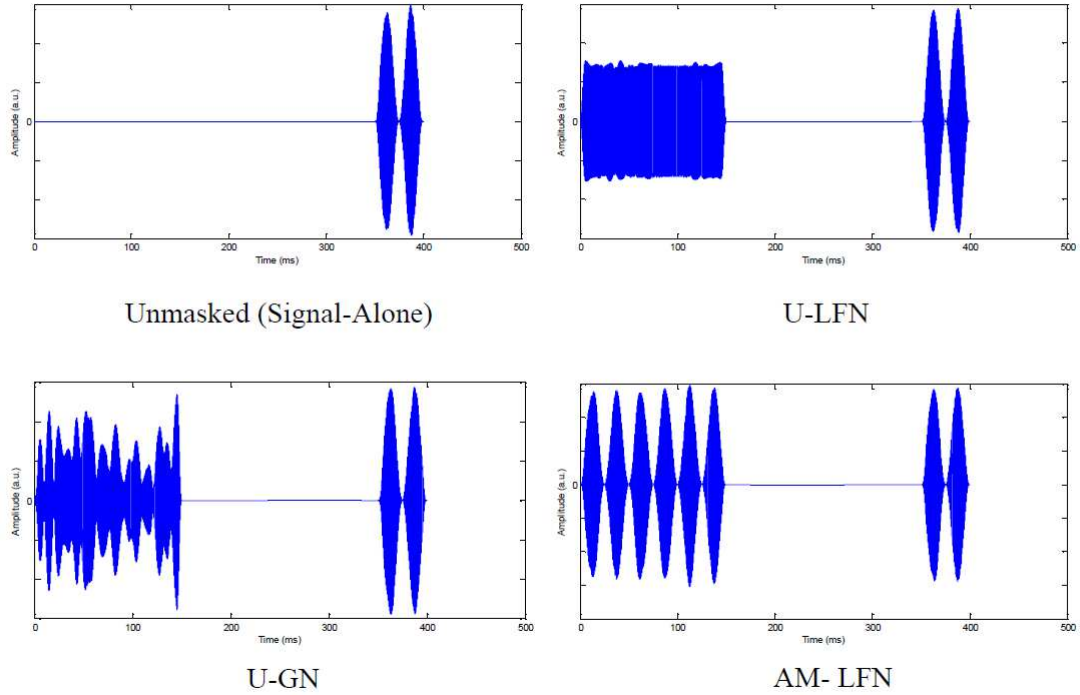


FIG. 4.3. Waveforms showing the brief 50-ms 40 Hz AM signal in each panel, including the unmasked condition (top left). The three types of 150-ms maskers are shown in the other three panels: unmodulated Gaussian noise (U-GN, bottom left); unmodulated low-fluctuation noise (U-LFN, top right); and 40 Hz AM low-fluctuation noise (AM-LFN, bottom right). The masker-signal delay for each masker condition is 200 ms.

C. Procedures

Both unmasked and masked MDTs were measured using a three-interval forced choice (3IFC), three-down, one-up, procedure adapting on signal modulation depth and tracking the 79.4% correct point on the psychometric function (Levitt, 1971). In the unmasked conditions, two intervals contained an unmodulated carrier, while the randomly-chosen third interval contained the AM signal. Six trials of detection thresholds

in the absence of an AM masker were measured to find unmasked thresholds and to acquaint the listener with the signal. In the masked conditions, all three intervals contained an AM masker, while only one randomly-chosen interval contained the AM signal.

Silent inter-stimulus intervals were 500 ms, and each interval containing the stimuli was time-locked to lights presented on a computer screen. Feedback consisted of the correct interval illuminating after the listener had made a decision. The modulation depth of the signal was set to 0 dB at the beginning of each trial, decreasing by 4 dB after two consecutive correct answers, and increasing by 4 dB after one incorrect answer. After four reversals, the step size was reduced to 2 dB until eight reversals were measured, completing the trial after a total of 12 reversals. MDTs were determined by the average of signal modulation depths over the final eight reversals. Three thresholds were gathered to estimate MDT for each condition. If MDTs exceeded 0 dB for any trials, resulting in artifacts of over-modulation influencing thresholds, these conditions were repeated. If over-modulation occurred after three repetitions, MDTs were not measured for that particular condition.

The stimuli were generated at a sampling rate of 44,100 Hz via MatLab on a PC matched with a Lynx TWO-B soundcard and a DAC1 D/A converter, and presented monaurally to the listener through a Tucker-Davis Technologies (TDT) HB6 headphone buffer driving a Sennheiser HD650 circumaural earphone.

For the continuous carrier conditions, the trials were blocked by center frequency (1000 or 4000 Hz) and randomized by a number assigned to each of the five conditions.

For the non-continuous carrier conditions, the trials were randomized by a number assigned to each of the four conditions. Due to the difficulty of the non-continuous carrier conditions for the majority of participants, listeners always completed the continuous carrier conditions before moving onto the randomization of the non-continuous carrier conditions. Testing did not exceed 8 hours over multiple visits, including informed consent, measurement of audiometric thresholds, data collection, and frequent breaks.

D. Data Analysis

To examine differences in masked thresholds between NH and HI listeners for the continuous carrier, effects of center frequency (1000, 4000 Hz) and masker-signal delay (50, 100, 200 ms) were assessed with a repeated-measures analysis of variance (ANOVA) in SPSS using the general linear model, including one between-subjects factor (NH vs. HI). For the non-continuous carrier results, each of the four conditions were treated as a level of a within-subjects factor (NM, U-LFN, U-GN, AM-LFN). Similar to the continuous carrier results, the effects of each condition were assessed with a repeated-measures ANOVA, including one between-subjects factor (NH vs. HI). Two listeners in each group were unable to complete the non-continuous carrier conditions, so their results were omitted from the corresponding ANOVA. Post-hoc tests for planned comparisons were used to determine differences between NH and HI listeners for U-LFN vs. U-GN, U-LFN vs. AM-LFN, and AM-LFN vs. U-GN, as well as for unmasked thresholds (continuous vs. non-continuous).

III. RESULTS

For the continuous carrier (see *Fig. 4.4*), gradual recovery from AM forward masking was observed for both groups. Results suggest there were main effects of center frequency [$F(1, 12) = 20.898$, $p < 0.05$] and masker-probe delay [$F(1, 12) = 58.518$, $p < 0.001$]. As predicted, masked MDTs improved as masker-probe delay increased.

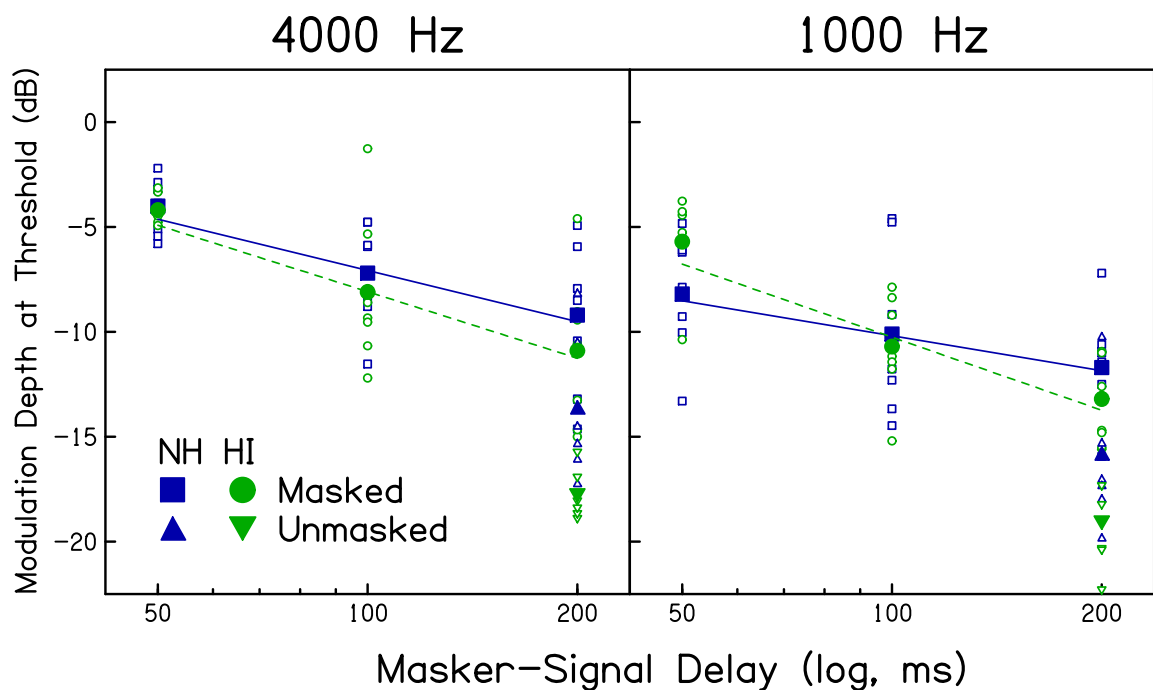


FIG. 4.4. Mean AM forward-masked modulation detection thresholds (MDTs), or modulation depth at threshold (in dB), for the low-fluctuation noise (LFN) continuous carrier conditions at two center

frequencies, 4000 (left) and 1000 (right) Hz, and at three masker-signal delays (50, 100, 200 ms) are plotted for NH (filled squares, solid lines) and HI listeners (filled circles, dashed lines). Mean unmasked MDTs for NH (filled triangles) and HI (filled inverted triangles) are plotted at a masker-signal delay of 200 ms. Individual masked and unmasked thresholds are plotted with the corresponding open symbols.

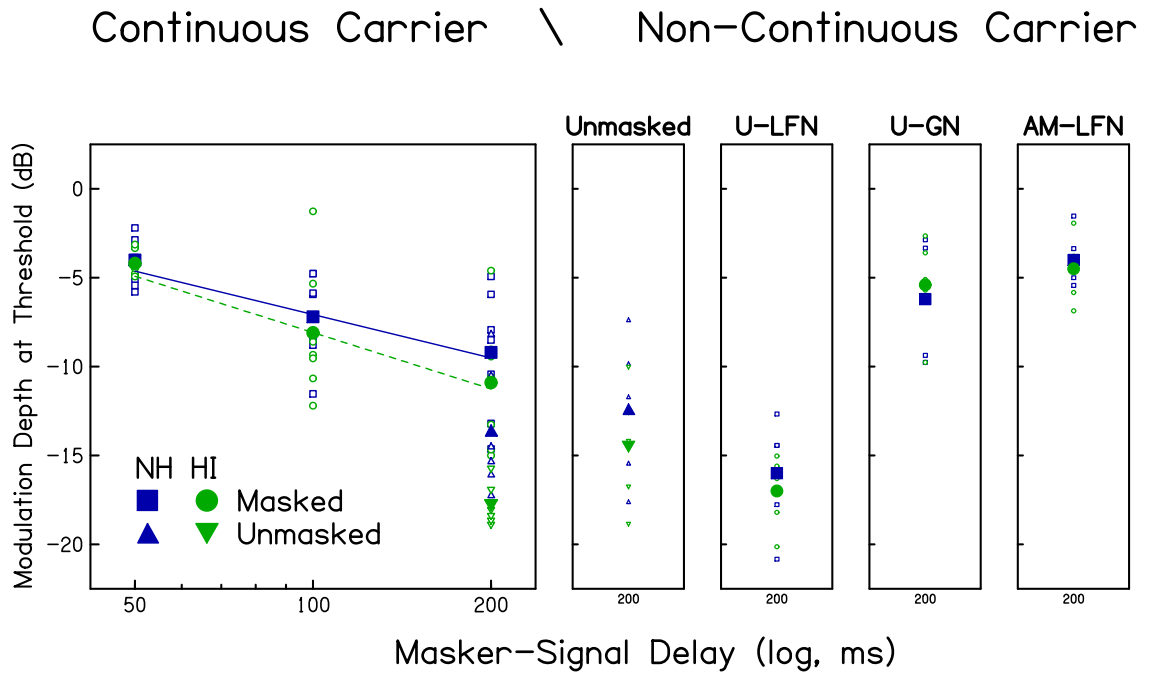


FIG. 4.5. Mean and individual AM forward-masked modulation detection thresholds (MDTs), or modulation depth at threshold (in dB), for the same continuous carrier conditions from Fig. 4.4. for 4000 Hz (first panel) at three masker-signal delays (50, 100, 200 ms) are plotted for NH (squares, solid lines) and HI listeners (open circles, dashed lines). For the non-continuous carrier conditions for 4000 Hz, the same symbols are used to plot MDTs for the Unmasked (second panel), unmodulated LFN masker (U-LFN, third panel), unmodulated GN masker (U-GN, fourth panel), and the 40 Hz amplitude-modulated LFN masker (AM-LFN, fifth panel) conditions.

Post-hoc tests for planned comparisons revealed that unmasked MDTs for the continuous carrier were significantly better for HI than for NH listeners at both 4000 ($p < 0.05$) and 1000 Hz ($p < 0.05$), which is consistent with previous reports (e.g., Bacon and Gleitman, 1992). There were no significant differences observed between NH and HI listeners for any of the masked conditions ($p > 0.05$).

Using paired comparisons across carrier types and within groups, no differences were observed between the unmasked thresholds for continuous and non-continuous carrier conditions for either NH or HI listeners ($p > 0.05$). However, when examining the effects of envelope fluctuations on forward masked MDTs, the U-GN masker yielded significantly more masking than the U-LFN masker ($p < 0.05$), and the U-GN and AM-LFN maskers produced comparable masking ($p > 0.05$). Again no differences were observed between listener groups ($p > 0.05$). These results suggest that masker envelope fluctuations were indeed contributing to the magnitude of AM forward masking, even at a masker-signal delay of 200 ms, and there was no apparent effect of hearing loss.

In addition, the non-continuous carrier yielded significantly more masking (NH = 5.4 dB, HI = 5.1 dB) than the continuous carrier when assessing the AM-LFN condition at a masker-signal delay of 200 ms for both NH ($p < 0.05$) and HI ($p < 0.05$) listeners.

These results suggest there are four primary effects of interest. First, masked MDTs improved as masker-probe delay increased for both groups. Second, for the non-continuous carrier conditions, the unmodulated GN yielded significantly more masking than the unmodulated LFN. Third, the continuous carrier resulted in better masked MDTs

for the AM-LFN condition than the non-continuous carrier at a masker-signal delay of 200 ms. Finally, in all conditions, HI listeners performed no worse than NH listeners, and in the absence of a masker, HI listeners out-performed the NH listeners.

IV. DISCUSSION

A. Primary Findings

As predicted for the continuous carrier conditions, significant AM forward masking was observed for both listener groups. Masked MDTs improved as the masker-signal delay increased, suggesting gradual recovery from AM forward masking, consistent with the results of Wojtczak and Viemeister (2005) and Wojtczak *et al.* (2011). However, neither group of listeners recovered to unmasked MDTs at a masker-signal delay of 200 ms, suggesting that the time constant of recovery from AM forward masking may be slightly longer than that for traditional forward masking (~120-200 ms; e.g., Jesteadt *et al.*, 1982; Ludvigsen, 1985).

As predicted for the non-continuous carrier conditions, the unmodulated GN yielded more masking than the unmodulated LFN, suggesting that inherent envelope fluctuations of the GN contributed to the amount of AM forward masking for both listener groups. In addition, comparable masked MDTs were measured for amplitude-modulated LFN and unmodulated GN, suggesting that the amount of AM forward masking yielded by either inherent envelope fluctuations or imposed envelope fluctuations, at least for these conditions, were quite similar.

Contrary to our predictions, hearing loss did not contribute to increased AM forward masking for HI listeners in either the continuous or non-continuous carrier conditions. In fact, HI listeners' unmasked thresholds were significantly better than those for the NH group. Although this result was initially unexpected, previous work has revealed a very similar effect in the absence of a masker. Bacon and Gleitman (1992) found that, at equal overall levels (dB SPL), unmasked MDTs were very similar for NH and HI listeners. At relatively low sensation levels, the authors showed that HI listeners performed significantly better than NH listeners, consistent with the unmasked MDTs measured in the current study. In contrast, the current study found that AM forward masking due to inherent envelope fluctuations (U-GN) or imposed envelope fluctuations (AM-LFN) was not elevated for HI relative to NH listeners at a masker-signal delay of 200 ms. Thus, it appears that hearing loss had very little effect on the magnitude or time constant of the recovery from AM forward masking for the conditions measured.

B. Possible Mechanisms

Recent work has shown that the auditory mechanisms responsible for the time constant of recovery from forward masking and AM forward masking may be essentially different. In the audio-frequency domain, probe signals undergo suppression by on-frequency forward maskers at the level of the IC (Finlayson, 1999), whereas, in the modulation-frequency domain, suppression is less apparent in IC neurons (Wojtczak *et al.*, 2011). This may partially explain why Svec *et al.* (2015^b) found differences in forward-masked detection thresholds due to inherent envelope fluctuations between NH

and HI listeners, while the current study found no differences between NH and HI listeners when assessing AM forward masking.

Counterintuitively, the amplitude-modulated LFN conditions resulted in better masked MDTs for the continuous carrier than the non-continuous carrier. The most likely possibility for this is that the envelope modulation imposed from gating the masker carrier resulted in excess masking. However, because unmasked thresholds for the continuous and non-continuous carrier conditions, as well as unmodulated masked MDTs for the non-continuous carrier, yielded such similar results within listener groups, some interaction of AM forward masking and cue disruption may have led to increased masking for the non-continuous carrier masked MDTs. An alternative consideration would be that the continuous carrier may have simply provided a more robust baseline for modulation detection relative to the non-continuous carrier. Additional investigation of the role of the carrier (continuous vs. non-continuous) will be necessary to uncover the underlying mechanisms.

Overall, based on these results it is likely that, at sufficiently audible levels, recovery from AM forward masking is not largely affected by hearing loss. This finding suggests that the influence of hearing loss on detection and use of envelope cues is multifaceted. For probe signal detection tasks, the persistence of listener uncertainty may largely account for the differences in additional masking observed between NH and HI listeners when comparing forward maskers with maximal vs. minimal inherent envelope fluctuations at longer masker-probe delays. However, both NH and HI listeners recover at similar rates and comparable time courses from AM forward masking.

V. CONCLUSIONS

- A. AM forward masking was observed for both HI and NH listener groups, with no difference between groups.
 - i. For the unmasked continuous carrier conditions, better MDTs were yielded for HI than NH listeners.
 - ii. For the masked continuous and non-continuous carrier conditions, NH and HI listeners performed very similarly, suggesting there is a little effect of hearing loss on the magnitude of AM forward masking.
- B. For the non-continuous carrier, the unmodulated GN yielded more masking than the unmodulated LFN, suggesting that inherent masker envelope fluctuations contributed to the amount of AM forward masking across listener groups.
- C. The continuous carrier resulted in better masked MDTs for the amplitude-modulated LFN masker than the non-continuous carrier, suggesting that AM forward masking is increased by the envelope modulation resulting from gating the masker carrier.

CHAPTER 5: SUMMARY OF RESULTS AND FUTURE DIRECTIONS

I. SUMMARY

Overall, this series of experiments has further illuminated the role of masker envelope fluctuations for both traditional forward masking and amplitude-modulated forward masking for listeners with normal and impaired hearing. Although the results

were not entirely intuitive and easily interpreted, several contributions to the literature, potential impact, and future implications are noted here.

A. Forward Masking

The results of Chapter Two demonstrated that forward maskers with greater inherent envelope fluctuations (Gaussian noise, GN) yielded higher masked thresholds than those with reduced inherent envelope fluctuations (low-fluctuation noise, LFN) for younger and older normal hearing (NH) listeners and older hearing-impaired (HI) listeners. These results suggest that the masking effects of inherent envelope fluctuations previously observed for simultaneously-masked pure tones (Kohlrausch *et al.*, 1997; Savel and Bacon, 2003) and speech recognition (Stone *et al.*, 2012) also occur in forward masking.

Contrary to predictions, the amount of masking yielded by noises that varied in their inherent envelope fluctuations did not change with hearing loss for a single masker-probe delay of 25 ms. If recovery from forward masking is dependent on neural mechanisms that determine the time constant (e.g., Oxenham, 2001), in combination with peripheral mechanisms (cochlear nonlinearities) that contribute to the slope of recovery (e.g., Oxenham and Moore, 1997), cochlear hearing loss should affect the slope of recovery due to reductions in peripheral nonlinearities, but the time constant should remain relatively intact (e.g., Oxenham and Bacon, 2003). For this reason, the authors asserted that measuring masked thresholds utilizing multiple masker-probe delays may reveal differences in slopes and time constants of recovery from the masking mechanisms

responsible for recovery from forward maskers with intact or reduced inherent envelope fluctuations.

After forward-masked thresholds for maximally (GN) and minimally (LFN) fluctuating maskers were measured at multiple masker-probe delays (25, 50, and 75 ms) for NH and HI listeners, the results of Chapter Three revealed differences between NH and HI listeners for recovery from variably fluctuating forward maskers. First, slopes of recovery from forward masking were shallower for HI than NH listeners, as predicted. Second, in regions of greater hearing loss, additional masking attributed to inherent masker envelope fluctuations (GN-LFN) was significantly larger for HI than NH listeners at the two longer masker-probe delays. However, at the shortest masker-probe delay, no significant differences in additional masking were observed between NH and HI listeners, which are consistent with the results from Chapter Two.

After initially interpreting the results from a traditional forward masking perspective, two types of further considerations were noted from the experiments in Chapters Two and Three:

- i. Envelope-Based Detection Cues: Temporal Onsets and Offsets

For a narrowband noise masker, a change in the temporal envelope, such as the onset of the probe, may lead to detection of the signal (Oxenham, 1998). Variability of inherent envelope fluctuations of the stimuli disrupt these cues, increasing listener uncertainty for a Gaussian noise more so than for a low-fluctuation noise masker (Buss *et al.*, 2006; Eddins, 2001). Lutfi (1990) estimated that a sizable portion (~ 22%) of the

masking observed for tone-in-noise experiments (simultaneous and forward masking) may be due to this listener uncertainty.

ii. Listener Uncertainty

For NH listeners in the forward masking domain, “confusion” between the offset of a narrowband masker and the onset of a sinusoidal probe that are separated by less than 20 ms has been reduced by additionally presenting a copy of the masker in the contralateral ear (Neff, 1986). This confusion has primarily been attributed to central factors, unaffected by peripheral hearing loss. Nonetheless, the results of Chapter Three revealed that a diotic forward masker significantly reduced differences between maskers with maximal vs. minimal inherent envelope fluctuations at a masker-probe delay of 75 ms for HI listeners. This suggests that listener uncertainty likely persists over a greater duration for HI than for NH listeners. Moreover, nearly half of the additional masking attributable to inherent envelope fluctuations was still observed for HI listeners after presenting a binaural cue, suggesting that a source other than listener uncertainty is likely also contributing to this additional residual masking.

B. Amplitude-Modulated Forward Masking

In Chapter Three, the authors speculated that amplitude-modulated (AM) forward masking may be contributing to some of the observed differences between forward maskers which have maximal or minimal inherent envelope fluctuations. If envelope-based detection cues were obscured by masker envelope fluctuations, then these disruptions may be partially related to AM forward masking (e.g., Wojtczak and Viemeister, 2005). Therefore, differences between NH and HI listeners due to inherent

masker envelope fluctuations in forward masking may include a combination of AM forward masking and listener uncertainty. The magnitude of listener uncertainty was quantified by measuring differences in masked thresholds for the monaural and diotic conditions from Chapter Three.

The purpose of Chapter Four, then, was to compare AM forward masking for listeners with normal and impaired hearing. AM forward masking was measured for both NH and HI listeners using continuous and non-continuous masker and signal carriers. Initially, a LFN carrier was used for the “continuous carrier” conditions to examine modulation masking yielded by a 40 Hz AM masker. To compare the amount of AM forward masking yielded by unmodulated LFN and GN maskers, as well as an AM LFN masker, additional conditions were included using a “non-continuous carrier.”

The results of Chapter Four revealed that AM forward masking was observed for both HI and NH listener groups, with no differences between groups. For the unmasked conditions for both carriers, better modulation detection thresholds (MDTs) were measured for HI than NH listeners. For the masked conditions for both carriers, NH and HI listeners performed similarly, suggesting the effect of hearing loss on AM forward masking was minimal for the conditions tested. For the non-continuous carrier conditions, the unmodulated LFN resulted in no elevation in masked MDTs relative to unmasked MDTs, suggesting that the unmodulated LFN was not contributing to AM forward masking. The inherently-fluctuating GN yielded significantly more masking than the unmodulated LFN, suggesting that inherent masker envelope fluctuations substantially contributed to the amount of AM forward masking across listener groups.

Somewhat unexpectedly, the continuous carrier resulted in better masked MDTs than the non-continuous carrier for the AM LFN masker, suggesting that either the envelope modulations imposed from gating the masker and the carrier on and off together resulted in additional masking, or that AM forward masking is decreased by cues associated with presence of a continuous carrier between the masker and the signal.

C. Mechanisms of Recovery from Forward Masking and AM Forward Masking

The time constant of recovery from forward masking and AM forward masking may arise from separate sources. When considered in the audio-frequency domain, pure-tone probes are suppressed by forward maskers through the activity of IC neurons (Finlayson, 1999), whereas, when considering AM forward masking in the modulation-frequency domain, suppression is less apparent at the level of the IC (Wojtczak *et al.*, 2011). This may partially explain why the results of Chapter Three revealed differences in traditional forward masking due to inherent envelope fluctuations between NH and HI listeners, while the results of Chapter Four found no differences between NH and HI listeners when assessing AM forward masking.

II. IMPLICATIONS FOR FUTURE DIRECTIONS

A. Probe and Modulation Detection

For detecting a pure-tone probe signal, the persistence of listener uncertainty may primarily explain the differences between NH and HI listeners for forward maskers with maximal vs. minimal inherent envelope fluctuations at longer masker-probe delays. Whereas, recovery from AM forward masking for NH and HI listeners is very similar,

suggesting that the slopes and time courses of recovery from AM forward masking are not largely affected by hearing loss.

However, when assessing forward masking, listeners are attempting to detect a signal as its level is reduced below threshold. In Chapters Two and Three, for NH listeners, where signal levels yielding forward-masked thresholds are low enough that cochlear compression is likely applied, the input-output functions for masker effectiveness may look quite distinct from those for HI listeners where signal level is elevated at threshold and cochlear processing is more linear (Oxenham and Bacon, 2003). These potential differences in the input-output functions for NH and HI listeners may partially contribute to differences in time course of recovery from inherent envelope fluctuations of the Gaussian noise. In addition, spectral and temporal detection cues may be more limited for HI than NH listeners, especially near threshold. To detect a pure-tone signal, NH listeners have been shown to attend to a local (within-filter) increase in energy (Green, 1967), across-channel comparisons of a change in level (Green, 1983), or changes in the temporal properties of the stimuli (Berg, 2004). There is a possibility that HI listeners have less robust cues for detection. If, by chance, HI listeners only have access to a sub-optimal cue relative to NH listeners, for a particular task (e.g., forward masking), perhaps thresholds will be elevated partially due to this sub-optimal cue. In other cases, where detection cues are just as robust, if not more so, for HI listeners relative to NH listeners (e.g., AM forward masking), perhaps this can account for some of the similarities in masked MDTs for the two groups.

For AM forward masking, the physical level of the signal is not changing, only its modulation depth. It has been shown that, likely due to a more linear response of the basilar membrane, HI listeners are often just as well equipped to detect amplitude modulations of a signal (Bacon and Gleitman, 1992; Moore and Glasberg, 2001). In this situation, the linear response of the basilar membrane may actually aid the HI listeners in attending to, or detecting, the peaks and valleys of subtle amplitude modulations. At an overall level of 80 dB SPL, both NH and HI listeners were subjected to stimuli that were well above hearing thresholds. This suprathreshold presentation may also be one of the keys to the differences between the results for Chapters Three and Four.

B. Relevance for Masking Release

As mentioned in Chapter One, it has been assumed that HI listeners may not recover after the offset of a noise masker at the same rate as NH listeners (e.g., Ludvigsen, 1985; Oxenham and Bacon, 2003). While this is clearly true in a general sense when considering slopes of recovery from forward masking, the current work has contributed to an important consideration when making this assumption. If a noise masker has a highly fluctuating temporal envelope, HI listeners will likely experience, not only a shallower slope of recovery than NH listeners after the offset of the masker, but also a longer time course of recovery to quiet threshold (e.g., Svec *et al.*, 2015^b). If a listener with hearing loss is attempting to detect or recognize a segment of speech after the offset of a duty cycle of an AM masker when the signal-to-noise ratio (SNR) is particularly unfavorable, this persistence of additional forward masking due to masker envelope fluctuations may play a role in the difficulty that HI listeners have relative to

NH listeners for speech-in-modulated-noise recognition, at least when measuring recognition near speech reception thresholds (SRTs). In addition, if listener uncertainty obscures a HI listener's ability to effectively attend to important signal attributes differently than for NH listeners, the persistence of listener uncertainty observed in Chapter Three may contribute to reduced speech-in-modulated-noise recognition, as well.

Although the results of Chapter Three revealed no differences between the listener groups, the additional AM forward masking yielded by an inherently fluctuating masker (GN) compared to a minimally fluctuating masker (LFN) suggests that these envelope fluctuations yield a substantial amount of sequential modulation masking. Perhaps an interaction between additional forward masking (GN-LFN), AM forward masking, and the persistence of listener uncertainty in between duty cycles of an AM masker will be able to account for a larger portion of the speech-in-modulated-noise recognition data than a simple correction for forward masking (e.g., Rhebergen *et al.*, 2006).

C. Remaining Questions

The most efficient way to confirm whether or not the findings measured in the currently considered work are relevant for differences in masking release between NH and HI listeners would be to replicate the conditions from Stone *et al.* (2012) for both listener types. If, as argued by Stone *et al.* (2012), the masking of speech produced by a Gaussian noise results mainly from the modulation masking yielded by rapid inherent envelope fluctuations, rather than energetic masking, then measuring “steady-state” and “amplitude-modulated” conditions for both GN and LFN would determine whether or not

the reduction of traditionally described masking release observed for NH listeners in the presence of LFN would also occur for HI listeners. Based on the results of the studies described in this manuscript, we predict that HI listeners would likely perform worse than their NH counterparts for the GN masker (see Chapter Three), but that performance would likely be similar for the LFN masker (see Chapters Three and Four).

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